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Recycled Concrete in Sustainable Architecture: A Comparative Study with Conventional Concrete.

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Abstract

A major contributor to global greenhouse gas emission has always been the construction sector. The major culprit at the heart of this sector is concrete. It is extensively used, high embodied carbon and extensively relies on virgin raw materials. The efficiency-driven design has significantly decreased the operational energy demands. With that, the relative significance of embodied carbon has also increased. This has shifted attention towards material selection as a critical tool for sustainable architecture. In this context, one potential strategy for reducing environmental impact is using recycled aggregate concrete (RAC) which also supports circular economy principles. However, concerns regarding durability, mechanical performance, professional risk perception, and regulatory constraints have limited the adoption of the recycled aggregate concrete (RAC) in architectural practices.

This study looks at the potential use of the recycled aggregate concrete (RAC) within architectural practices, as a replacement for conventional concrete (NC). It synthesizes peer reviewed experimental research, European technical framework, and life-cycle assessment (LCA) studies to evaluate RAC performance across three dimensions: mechanical behavior, durability response, and embodied-carbon impact. This study uses a structured analytical framework approach in order to interpret existing evidence rather than presenting new experimental data. This approach will make this study traceable, reproducible, and in fact applicable to architectural material specification.

This study will show that when recycled aggregate concrete (RAC) is used at partial replacement levels typically up to 30-50 percent, these recycled aggregates concrete can achieve mechanical performance similar to conventional concrete. Of course, the aggregate quality, mix design, and curing practices have to be appropriately controlled to get the desired results. It has been consistently reported that using the RAC causes reduction in elastic modulus and increased sensitivity to durability related transport mechanisms. However, these effects are shown to be conditional rather than inherent. As such, they can be dealt with through informed design and specifications strategies. From an environmental perspective, cradle to gate life cycle assessments (A1-A3 modules of EPD) clearly show that when sourced locally, RAC offers meaningful embodied CO_2 reductions ranging between 15-25 % per cubic meter of concrete. This result highlights the importance of regional circular supply chains. The thesis identifies an optimal substitution range in which performance tradeoffs are balanced against sustainability benefits. To get these findings mechanical, durability, and environmental considerations were integrated into a unified interpretative framework. The findings reposition recycled aggregate concrete as a strategic design choice rather than just a direct material substitute, and challenge the perception that RAC is an inferior material. Ultimately, this research argues that sustainability in architecture does by no means suggest abandoning concrete, but rather examines how it is produced and incorporated into a recycling material system.

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Nomenclature

Symbol / Acronym	Full Term / Description
A1–A3	Product stage life-cycle modules: raw material supply, transport, and manufacturing (EN 15978)
ANN	Artificial Neural Network
ASTM	American Society for Testing and Materials
BAU	Business-As-Usual scenario
BIM	Building Information Modeling
CDW	Construction and Demolition Waste
CO_2	Carbon Dioxide
EPD	Environmental Product Declaration
EU	European Union
GWP	Global Warming Potential
ITZ	Interfacial Transition Zone
LCA	Life Cycle Assessment
NC	Natural (Conventional) Concrete
NCA	Natural Coarse Aggregate
NA	Natural Aggregate
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RAC	Recycled Aggregate Concrete
RA	Recycled Aggregate
RCA	Recycled Concrete Aggregate
RCP	Recycled Concrete Powder
RPC	Recycled Powder Concrete
SCM	Supplementary Cementitious Material
SSD	Saturated Surface-Dry condition
w/c	Water-to-Cement ratio
fc	Compressive strength of concrete
ft	Tensile strength of concrete
flex	Flexural strength of concrete
E	Elastic modulus (Young's modulus)
kg/m^3	Kilograms per cubic meter
MPa	MegaPascal
GPa	GigaPascal
Carbonation depth	Depth of carbonation front penetration in concrete
Chloride diffusion coefficient	Measure of chloride ion penetration through concrete
Freeze–thaw resistance	Ability of concrete to withstand repeated freezing and thawing cycles
Permeability	Ability of concrete to allow fluid penetration
Porosity	Volume fraction of voids in concrete or aggregates
Water absorption	Percentage increase in mass due to water uptake
Cradle-to-gate	Life-cycle boundary from raw material extraction to factory gate
Embodied carbon	Total greenhouse gas emissions associated with a material over its life cycle

Symbol / Acronym	Full Term / Description
Functional unit	Reference unit for LCA comparison (1 m^3 of concrete in this thesis)
Module D	Benefits beyond the system boundary (reuse, recycling, recovery)
Rc	Concrete and mortar constituents (EN 933-11 classification)
Ru	Unbound natural stone
Rb	Masonry materials (bricks, tiles)
Ra	Bituminous materials (asphalt)
Rg	Glass
X	Other materials (wood, plastics, gypsum, metals, etc.)
ITZ_1	Interface between natural aggregate and new cement paste
ITZ_2	Interface between natural aggregate and old adhered mortar
ITZ_3	Interface between old adhered mortar and new cement paste
Local sourcing scenario	Aggregate transport distance ≤ 30 km
Extended sourcing scenario	Aggregate transport distance ≥ 80 km
Replacement ratio	Percentage of natural aggregates replaced by recycled aggregates
C30/37	Concrete strength class (30 MPa cylinder / 37 MPa cube strength, EN 206)

1 Introduction

The built environment is central to discussions on sustainability, particularly as urban populations expand and infrastructure demands increase, leading to significant environmental challenges.

Concrete, a predominant material in this sector, and essential to modern construction is also a major contributor to environmental degradation. Its extraction is a resource intensive process and contributes to high carbon emissions and significant waste generation. Being the most widely used construction material in the world, concrete plays a major role in the physical landscapes and also influences construction practices. Both engineers and architects struggle to find a balance between the urgent need to use concrete and the need for sustainable solutions.

Historically, sustainability in architecture has mostly concentrated on optimizing operation energy which included improving insulation, minimizing heating and cooling demands, and integrating renewable energy sources (Knoeri et al., 2013; Mainkovic et al., 2017). Embodied carbon has recently taken the spotlight which led to reexamining the materials used in the built environment. Embodied carbon refers to the total greenhouse gas emissions associated with materials over their life cycle. This includes extraction, production, transportation, construction, and end of life disposal (Colangelo et al., 2018; Pavlů et al., 2019). Studies have shown that sometimes the majority of the total life cycle environmental impact is significantly made up by embodied carbon, especially in energy efficient buildings. This fact highlights the importance of material selection in sustainable design (Colangelo et al., 2020; Mostafaei et al., 2023).

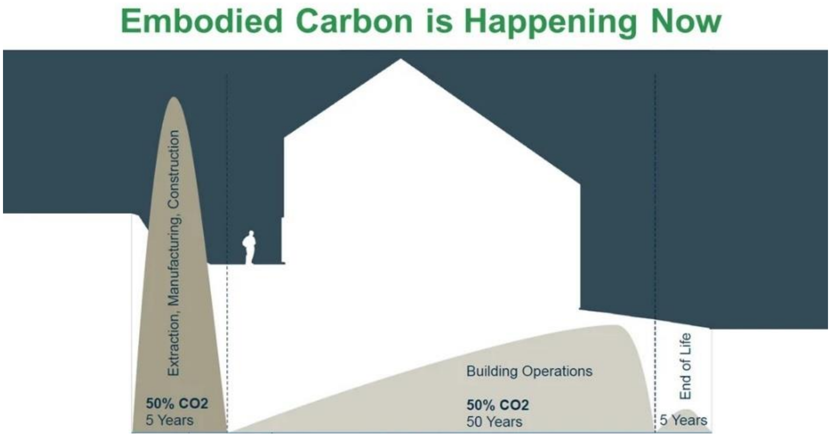


Figure 1 Conceptual comparison between operational carbon and embodied carbon contributions over a building life cycle. Results show the increasing relative importance of material-related emissions in energy-efficient buildings.(Carroll, 2025)

Figure 1 illustrates the balance between operational and embodied carbon in contemporary buildings. The results show that improving the building energy efficiency significantly reduces operational emissions that traditionally dominated life cycle impacts. This means that emissions associated with materials, construction processes, and end of life phases have become much more significant. This shift clearly indicates that when focusing on sustainable architectural design embodied carbon should be addressed through material selection focusing on concrete.

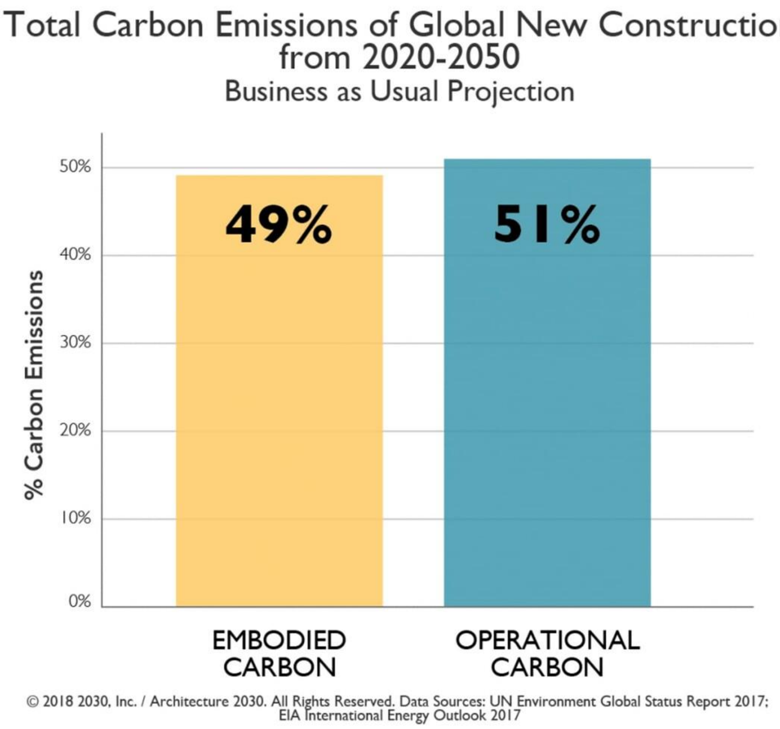


Figure 2 Relative contribution of embodied and operational carbon to total carbon emissions from global new construction between 2020 and 2050 under a business-as-usual scenario (Farbman, 2022)

Figure 2 shows the projected distribution of carbon emissions from global new construction between 2020 and 2050, assuming no major strategic changes. The figure shows that the embodied carbon is approximately equal to the carbon emissions generated during the operational phase of the building. This projection reveals a important turning point in sustainability thinking. Although operational efficiency improves, emissions associated with materials, construction processes, and end of life stages remain substantially high. From an architectural point of view, this means that the issue of embodied carbon should be dealt with through material selection and design strategies. This highlights directly concrete which is a high impact material.

Concrete's role in sustainability is complex; while it offers structural versatility and efficiency, it is also one of the most carbon-intensive materials, primarily due to the energy-intensive cement manufacturing process and the extraction of natural aggregates (Ding et al., 2016; García-Segura et al., 2013). Additionally, the construction sector produces vast amounts of construction and demolition waste (CDW), which constitutes a major landfill contributor, thus contradicting the principles of sustainability and resource efficiency advocated by initiatives such as the European Green Deal and the Circular Economy Action Plan (Collins, 2010; Lynch, 2022). These frameworks promote transformative practices in construction, aiming for waste valorization, decreased reliance on virgin resources, and the fostering of circular material flows (Colangelo et al., 2020; Marathe et al., 2025).

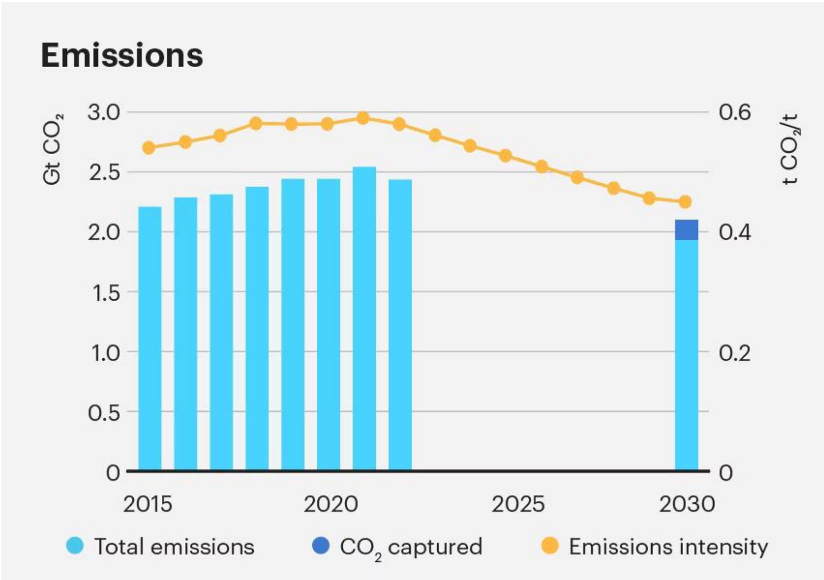


Figure 3 Global CO_2 emissions attributed to cement production, highlighting the increasing contribution of cement to global anthropogenic emissions (*IRENA & UN Climate Change High-Level Champions*, 2023)

Figure 3 shows how global cement production is responsible for the scale and persistence of carbon dioxide emissions. Both energy intensive kiln operations and the chemical process of limestone calcination, used in the production of cement, are responsible for the significant and growing share of anthropogenic CO2 emissions. This goes directly to show that concrete cannot be treated as an environmentally neutral material when used in architectural practice. On the contrary, the evidence shows that concrete should be at the heart of any contemporary sustainability debate, especially in the early stages of design when materials selection decisions are made.

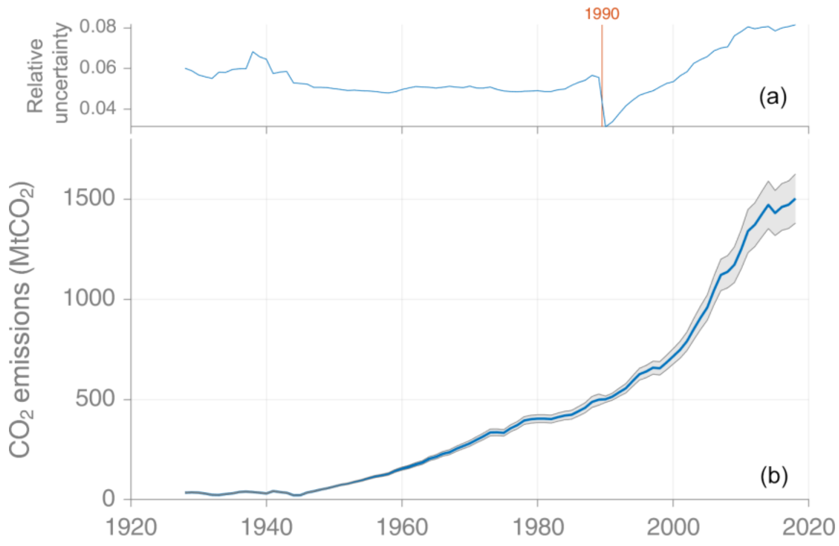


Figure 4 Global CO_2 emissions from cement production over time, showing historical trends and associated uncertainty ranges. The upper panel illustrates relative uncertainty, while the lower panel presents total cement-related CO_2 emissions (Andrew, 2019)

Figure 4 presents the historical evolution of carbon dioxide emissions associated with global cement production, based on a comprehensive dataset compiled by (Andrew, 2019). The lower panel shows that from mid-20th century onward, there is a steady increase in cement related CO2 emissions. This is due to the rapid expansion of urbanization, infrastructure development, and concrete use worldwide. As seen in the upper panel, the relative uncertainty associated with emission estimates remains limited in comparison to the overall magnitude and upward trajectory of emissions. When combining the data of the two panels, it becomes evident that cement production is a major and steady contributor to embodied carbon. From an architectural point of view, the figure provides strong empirical evidence suggesting that a major emphasis should be put on the material selection stage, especially when addressing the concrete related emissions. The choice of material during the design decisions plays a major role on the environmental impact of the built environment.

In this context, replacing natural aggregates with recycled aggregates sourced from CDW, RAC has the potential to significantly reduce embodied carbon, decrease resource extraction, and divert substantial amounts of waste from landfills (Colangelo et al., 2018; Santero et al., 2013). RAC addresses many of the sustainability challenges which make it a viable alternative to use.

Research has shown that when designed appropriately, RAC can achieve or even surpass the mechanical and durability performance of conventional concrete, challenging the notion that it is an inferior option (Marinković et al., 2017; Xiao et al., 2020). However, despite these benefits, the practical application of RAC in architectural settings remains limited due to concerns about performance variability, regulatory hurdles, economic feasibility, and professional attitudes that often view recycled materials as substandard (Knoeri et al., 2013; Zheng et al., 2025).

A major disconnection between what is available in technical advancements and the real implementation in architecture exposes a major gap in current practice. The existing literature on recycled concrete comes from engineering and materials science, which tend to concentrate on performance metrics rather than providing little support for architectural decision making (Pavlů et al., 2019; Ramirez & De Belie, 2023). By investigating the common points between material science, environmental impact assessment, and architectural practice, this thesis aims to address this gap and come up with resolutions addressing this issue.

Through a synthesis of peer-reviewed literature, standardized European data, and life cycle assessment (LCA) studies, this research aspires to guide architectural decision-making with context-sensitive evaluations that underscore opportunities for effectively incorporating recycled materials into sustainable design frameworks (Martínez-Arguelles et al., 2019; Patrisia et al., 2025). By reframing RAC as a viable design option rather than a lesser alternative, this thesis aims to contribute substantially to discussions on sustainable architecture and circular construction, positing that mitigating the environmental impact of concrete requires not rejection but a thoughtful reassessment of its production, specification, and role in architectural practice.

2 Conceptual Framework and Research Context

2.1 Research Aim, Objectives, and Questions

This section serves to formally conclude Chapter 2 by outlining the specific aims, objectives, and research questions guiding this thesis.

- Aim:
  - To critically evaluate the implications of incorporating recycled concrete in architectural design while addressing sustainability concerns.

- Objectives:

  - To analyze the environmental benefits of recycled concrete vis-à-vis traditional concrete in a lifecycle context.
  - To explore barriers influencing architects' decisions to adopt recycled materials.
  - To provide a framework for the informed selection of materials that align with sustainability goals in architecture.

- Research Questions:
  - How does the adoption of recycled concrete influence environmental sustainability in architectural projects?
  - What barriers impede architects from utilizing recycled aggregates in their designs?
  - In what ways can architects be supported to make informed material choices that align with sustainability frameworks?

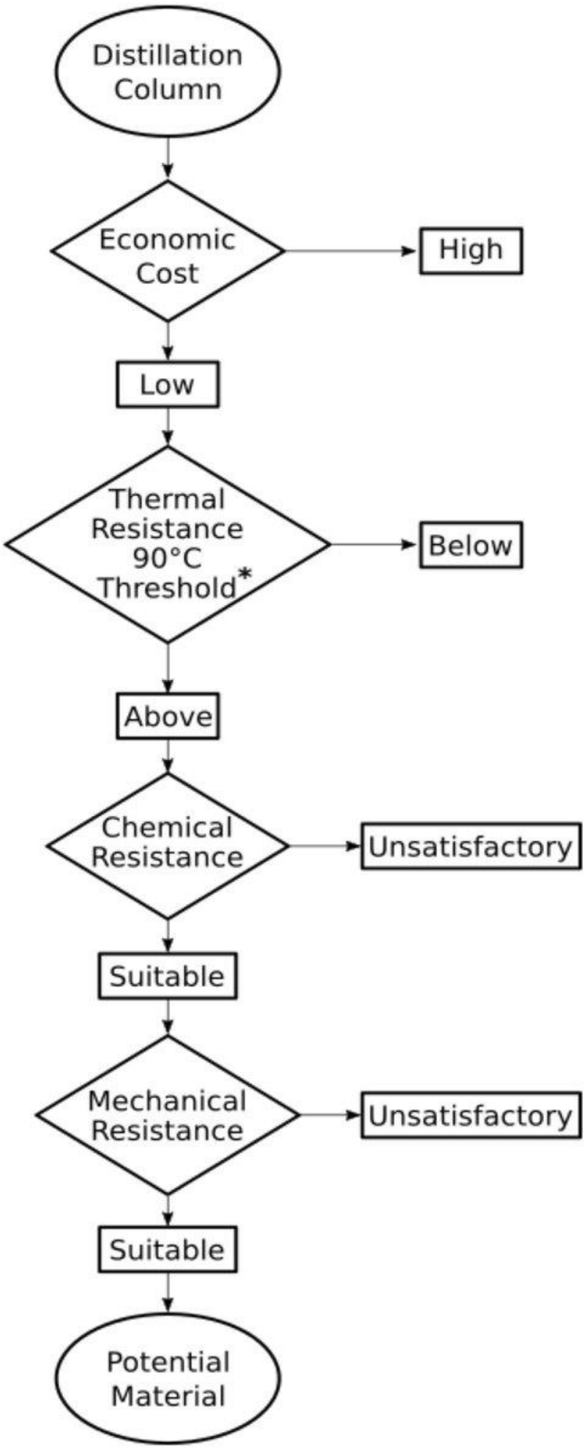
2.2 Concrete as an Architectural Material

This section aims to look at concrete not just as a construction material but to position it as a critical design decision within architectural practice. When addressing sustainability, concrete needs to be looked at as more than just a default choice but needs thoughtful exploration of its implications in contemporary architecture.

Concrete is most often approached as a neutral material, chosen primarily for its structural properties and versatility. Historically, its strength and durability have largely dictated its widespread use across the built environment. However, as sustainability emerges as a fundamental concern within architectural discourse, there is an imperative to reevaluate this perception. Architects cannot treat concrete as a simple, interchangeable material but must acknowledge and engage with its complex environmental impacts (Colangelo et al., 2018; Ding et al., 2016).

The relationship between structure, form, and material choice becomes increasingly significant. Architects must incorporate an understanding of how concrete contributes to ecological degradation, particularly regarding its production processes, which are associated with considerable carbon emissions (Yehia et al., 2015). This paradigm shift necessitates a design philosophy where materiality is integrated into early conceptual stages of the project lifecycle, fostering a more responsible approach to material use (Jin et al., 2018). By navigating this complexity, architects can move towards a more informed perspective on concrete, utilizing its properties strategically rather than by default. Material adoption in architecture often follows a sequential evaluation logic, where economic and performance thresholds act as filters rather than absolute enablers (Figure 5).

Figure 5 illustrates a framework for choosing a material in a sequential evaluation process and not an automatic choice. This method of sequential evaluation or progressive filtering is based on economic and performance criteria, and it is directly applicable when making architectural material choices. This is especially true when it comes to concrete and this reinforces the argument that materiality should be actively questioned and assessed in early design stages. If material selection becomes a structured decision-making process, then from the figure it is evident that concrete should stop being looked at as a neutral construction material but rather a strategic architectural choice that has major environmental and design implications.



*An exception was made regarding the HDPE.

Figure 5 Conceptual decision-based framework illustrating how material selection follows a sequential evaluation process based on economic feasibility and performance-related criteria rather than default adoption. (Cunha et al., 2020)

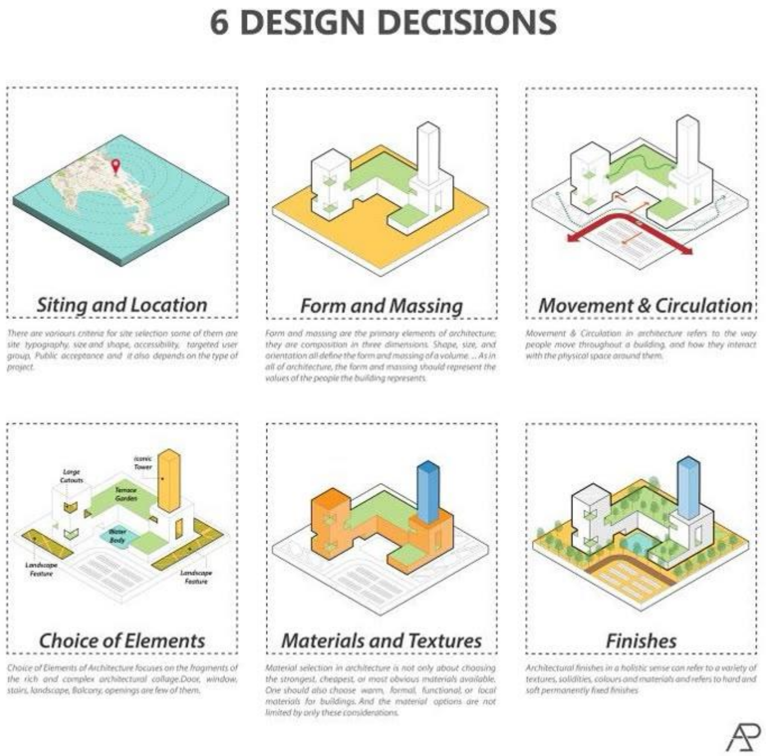


Figure 6 Key architectural design decisions influencing the built environment, illustrating how material selection operates alongside site, form, circulation, and finishing strategies within the architectural design process.

Figure 6 places material selection as an intricate part of architectural decision making. It is considered alongside with sitting, form and massing, circulation, and finishes. Instead of treating material choice as purely a technical matter or a secondary concern, it becomes at the heart of the creation or the conceptual work. It is approached same as spatial organization and architectural expression. As such, concrete and recycled aggregate concrete must be addressed not only as an element in the structural solution. Concrete and RAC should be used as a design element that shapes environmental performance, spatial quality, and architectural intent. When considered as such, the argument that was addressed in Section 2.2 states that concrete should not be considered a neutral construction choice, but as a strategic architectural material. That means that when addressing the choice of material, the decision should not be taken in isolation. It should be addressed as one of several interdependent architectural decisions that together they shape the environmental and spatial outcome of a project.

2.3 Sustainability in Architecture: From Performance to Responsibility

The purpose of this section is to reframe the concept of sustainability in architecture as an ethical and strategic obligation, extending beyond mere technical optimization to encompass a broader responsibility during the design process. This broader understanding of sustainability can be framed through interconnected economic, social, and environmental dimensions rather than isolated performance metrics (Figure 7)

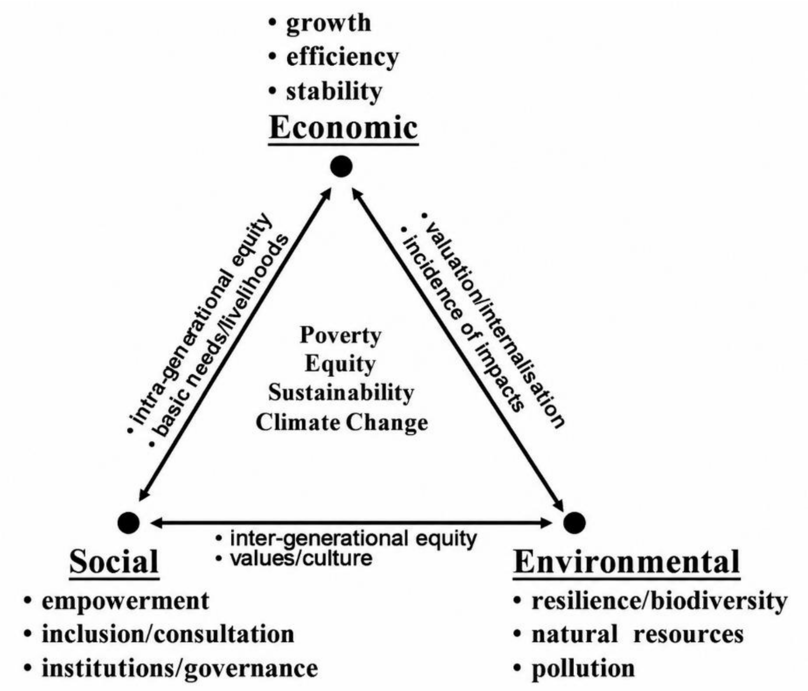


Figure 7 Three-pillar sustainability framework illustrating the interdependence between economic, social, and environmental dimensions, with equity, poverty, and climate change positioned as cross-cutting challenges.(Munasinghe, 2007)

Figure 7 shows that sustainability is dependent on three dimensions: economic, social, and environmental. Instead of looking at sustainability as a purely technical or environmental issue, the figure shows that long term stability depends on economic viability, social equity, and environmental resilience. In the context of architecture, this approach dictates that sustainable design decisions including material selection, must take into consideration more than performance optimization to cover broader ethical and social responsibilities.

By locating climate change and equity as cross-cutting concerns, the figure supports the repositioning of sustainability as a strategic and value-driven obligation within architectural practice.

Achieving sustainability in architecture, therefore, depends not only on balancing environmental, social, and economic dimensions, but also on how responsibilities are distributed and coordinated within the design process (Figure 8).

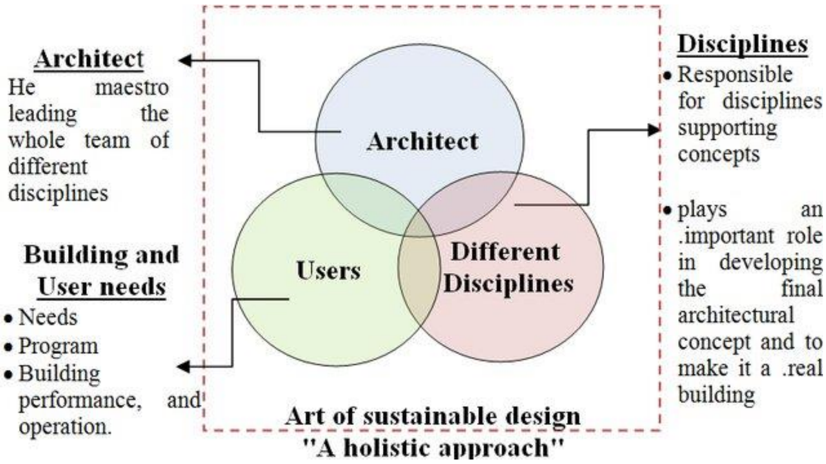


Figure 8 Conceptual representation of sustainable architectural design as an integrative process involving architects, users, and supporting disciplines, highlighting the central coordinating role of the architect. (A. Farid, 2015)

Figure 8 shows that sustainable architectural design is dependent on the interaction between architects, users, and multiple supporting disciplines. The diagram highlights the role of the architect as the coordinator between user needs, technical inputs, and disciplinary expertise in order to come up with a coherent design strategy. Within the context of sustainability, this diagram shows that a single technical domain cannot be responsible for environmental and material outcomes. Instead, when deciding on the use of concrete or recycled concrete aggregates for example, the decision should be taken based on the coordination of the architect between performance requirements, user expectations, and sustainability objectives. Traditionally, efforts in sustainable architecture have concentrated on optimizing operational performance, reducing energy consumption, improving insulation, and integrating renewable energy solutions into building designs (Schepper et al., 2014). However, this perspective is limited; it neglects the significant factor of embodied carbon, which incorporates the life cycle of materials from raw extraction to end -of-life disposal (Collins, 2010)

Architects must realize their impact during initial design phases, where material selection becomes a deeply impactful decision. Each material chosen carries implications for resource depletion, waste generation, and carbon emissions, as architects transition from mere facilitators of design to stewards of environmental responsibility (Arvizu-Montes et al., 2025).

When material selection is viewed through an ethical lens, the importance of sustainable choices can guide decisions that reflect a commitment to reducing environmental footprints. This emphasizes the notion that sustainability in architecture necessitates an integrated approach, identifying materials like concrete as key constituents in achieving ecological goals (Ghosn et al., 2023).

2.4 Embodied Carbon and Life Cycle Thinking

This section introduces a basic understanding of the concept of life cycle assessment (LCA) and embodied carbon. Embodied carbon encompasses the total greenhouse gas emissions generated over a material's life cycle, which includes raw material extraction, production, transportation, construction, maintenance, and disposal phases (Moro, 2023). It is crucial to understand the environmental impact of construction materials like concrete, because it has a considerable carbon footprint due to cement production. Therefore, in order to assess life cycle, it is important to define system boundaries which include material processing, transportation, and end of life scenarios, as illustrated in Figure 9.

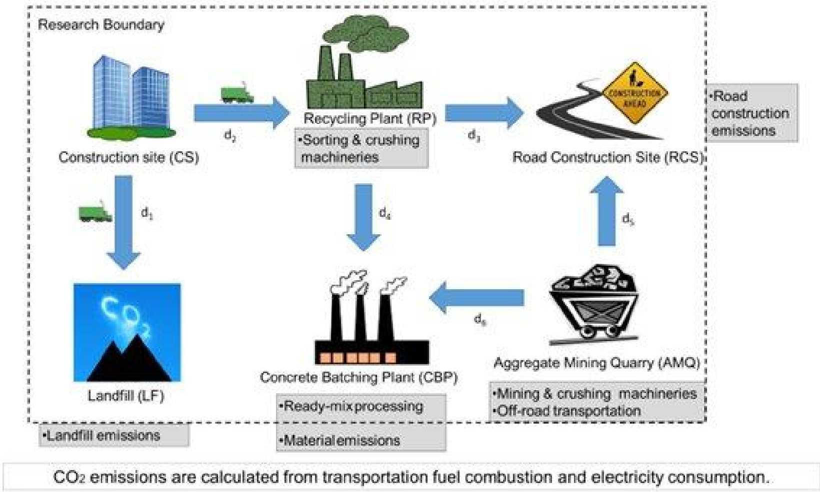
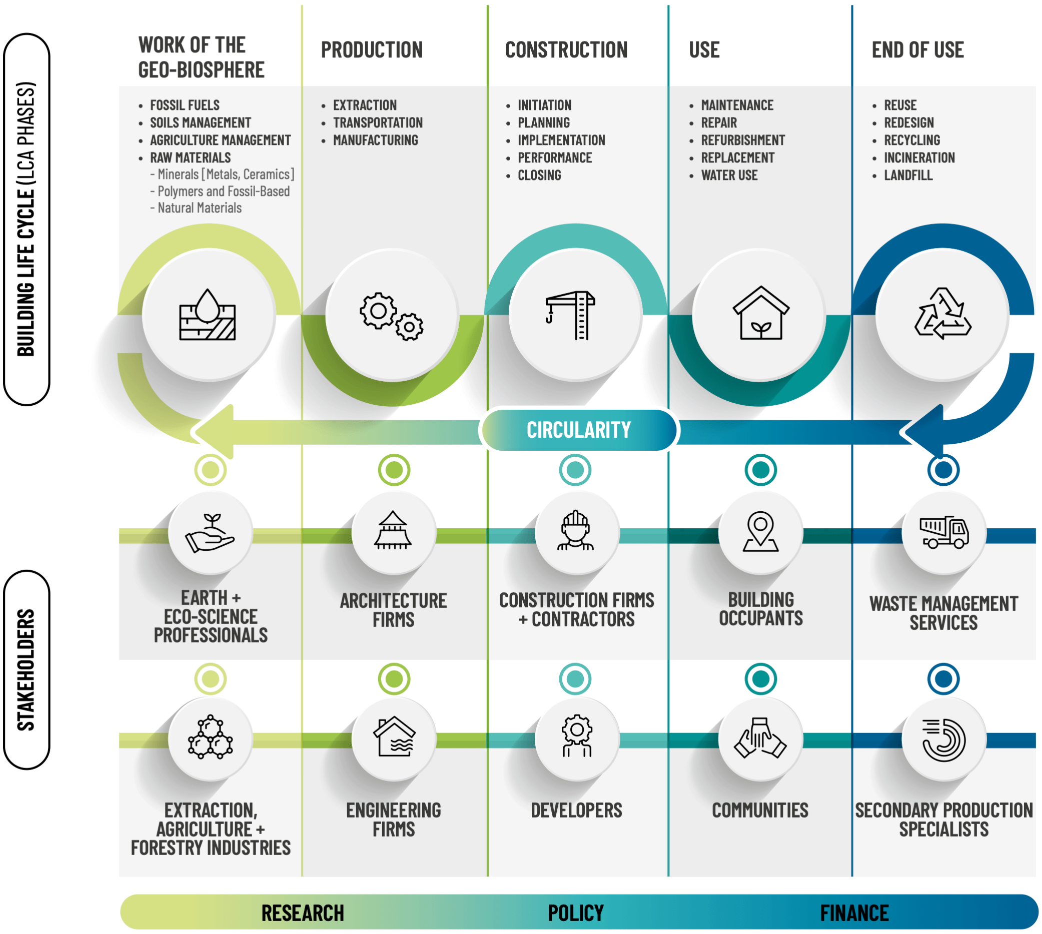


Figure 9 System boundaries and material flow considered in the life-cycle assessment of concrete production, illustrating transportation stages, processing facilities, and associated CO_2 emission sources across the construction supply chain.(Mah et al., 2017)

Figure 9 shows the multiple stages at which carbon dioxide emissions are generated in the life cycle assessment of concrete. The diagram traces the movement of materials from aggregate extraction and recycling facilities through concrete batching plants and construction sites. It also takes into account the emissions from transportation, processing and land filling. By visualizing these interconnected stages, the figure clarifies how embodied carbon accumulates across the supply chain rather than originating from a single source.

In the context of this thesis, the figure reinforces the importance of life cycle thinking in architectural decision-making and supports the argument that material choices—such as the adoption of recycled aggregate concrete—can significantly influence embodied emissions through reduced extraction, shorter transport distances, and altered processing pathways. Because embodied carbon is generated across multiple life-cycle stages, its reduction depends on coordinated decisions among a wide range of stakeholders rather than isolated technical interventions (Figure 10).

2.7 Key stakeholders whose participation is critical to the decarbonization of buildings at different life phases



They include scientists; architecture, engineering and construction firms; building occupants; and waste management and recovery professionals.

Adapted from Keena and Dyson 2017; Keena et al. 2023..

Figure 10 Key stakeholders involved in the decarbonization of buildings across different life-cycle phases, illustrating the distribution of responsibilities from material extraction and production to use and end-of-life stages. (Keena & Dyson, 2017)

Figure 10 maps the building life cycle against the stakeholders whose participation is critical to reducing carbon emissions at each stage, from raw material extraction and production through construction, use, and end-of-life processes.

The figure shows that embodied carbon comes from a network of decisions involving engineers, contractors, material producers, policy makers, and waste management professionals. In the context of this thesis, the figure clearly shows that architectural material choices such as the use of recycled aggregate concrete, are dependent on social and technical systems. Although architects play a major coordinating role, it is not enough to reduce embodied carbon. The reduction comes from the alignment across disciplines, regulatory frameworks, and supply chains. This supports the need for life cycle thinking and collaborative approaches when it comes to material sustainability in architectural practice. Important to note that LCA serves as a tool to quantify these emissions and guide design decisions. Knowledge of the full environmental costs associated with materials is necessary for architects to make informed choices that resonate with sustainable practices (Collins, 2010). However, looking only at performance metrics often discard the broader implications of material use. This will impede the efforts to comprehensively address sustainability.

As such, architects must embrace life cycle thinking as a vital component of the design process, recognizing that decisions made at the design phase have lasting impacts on environmental and social outcomes (Govardhan & Venkataraman, 2023).

2.5 Circular Economy and Construction Materials

In this section, the objective is to align the thesis with European Union policy frameworks relating to sustainability and the circular economy, highlighting their implications for architectural practices. Circular economy principles propose a systemic reorganization of material flows aimed at retaining value and minimizing waste across production and consumption cycles (Figure 11).

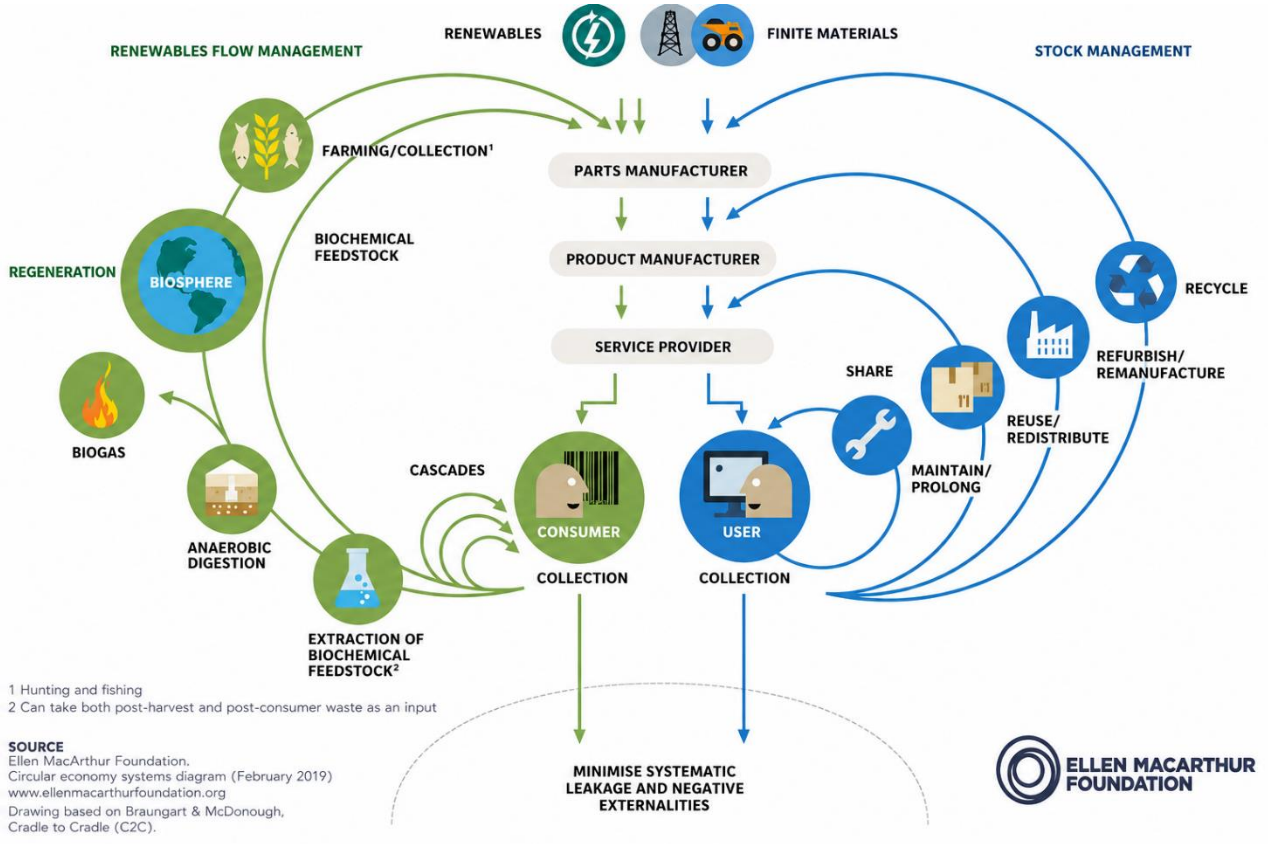


Figure 11 Circular economy system diagram illustrating biological and technical material cycles, emphasizing reuse, refurbishment, remanufacturing, and recycling as strategies to minimize waste and reduce resource extraction. (Dsilva et al., 2023)

Figure 11 presents the circular economy framework as a systemic model in which material flows are organized to retain value, minimize waste, and reduce reliance on virgin resource extraction

The diagram shows the differences between biological and technical material cycles. It addresses different alternatives to linear production and disposal pathways, such as reuse, refurbishment, re manufacturing, and recycling. When it comes to construction materials, this model highlights the importance of maintaining materials at their highest possible value for as long as possible. Which means that recycled aggregate concrete fits perfectly within the definition of this model. By re-using construction and demolition waste back into productive use, land filling is reduced and so are the environmental impacts associated with raw material extraction. The figure confirms the thesis argument that isolated material substitutions is not enough. The adoption of circular material strategies in architecture requires systemic thinking.

The construction and demolition waste (CDW) represent a significant obstacle to sustainability in architecture. Vast quantities of materials are discarded, contributing to landfills and resource depletion. European Union policies advocate for circular economy principles, which prioritize reusing and recycling materials and reducing reliance on virgin resources (Ding et al., 2025).

These principles demand a shift in construction practices, urging architects to actively participate in these transformations. Circular economy principles in the built environment must therefore be understood as life-cycle strategies that begin at the design stage and extend through construction, operation, and end-of-life processes (Figure 12)

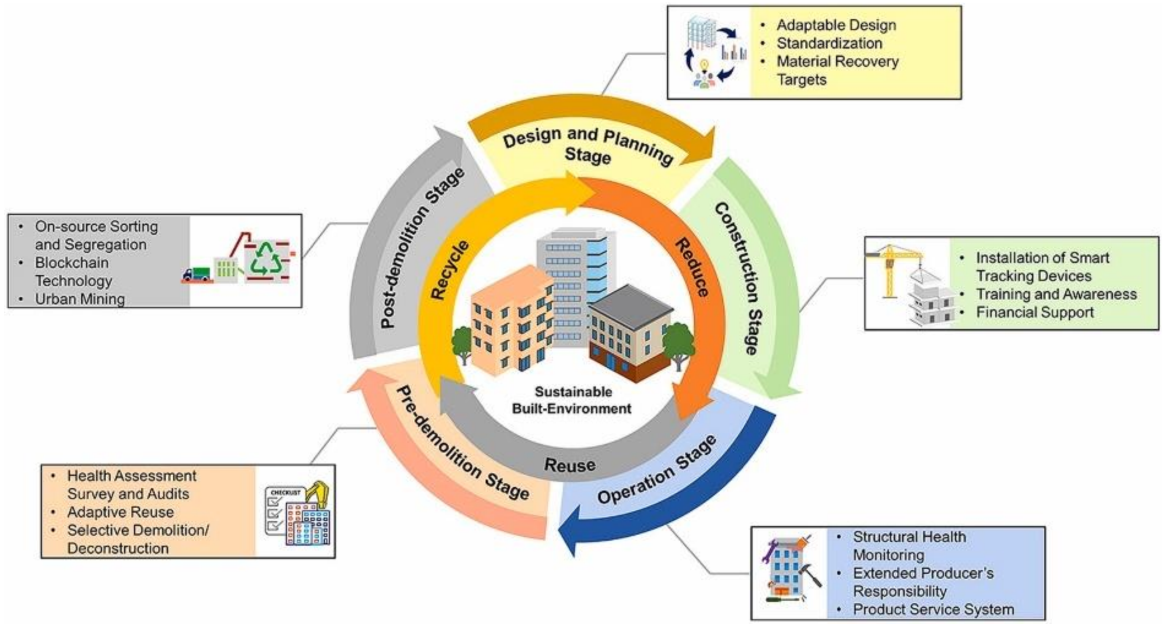


Figure 12 Circular economy strategies applied across the life-cycle stages of the built environment, illustrating design, construction, operation, reuse, and demolition phases and their role in achieving a sustainable built environment. (Sharma et al., 2022)

Figure 12 shows how circular economy principles can be applied across the entire life cycle of the built environment, which included design, planning, construction, operation, reuse, and post demolition stages. The diagram shows that circularity does not only come to play at the end of life as a recycling step. In fact, circularity is affected by decisions made during the early design stages, when addressing adaptable design, standardization, and material recovery targets. The figure highlights the potential to retain material value and reduce waste generation throughout a building's lifespan. This is achievable by integrating strategies such as reuse, selective deconstruction, and urban mining. In the context of this thesis, the use of recycled aggregate concrete fits the circular economy principles perfectly. It brings together design intent with end-of-life material recovery and reuse.

By adopting circular economy strategies, architects can help mitigate the CDW problem through innovative design approaches that consider material regeneration and waste minimization from the outset (Moro et al., 2025).

The transition towards circularity aligns with sustainable practices that not only enhance environmental performance but also drive economic viability by creating new opportunities for resource efficiency and waste valorization (Ying, 2025).
This section underscores the necessity for architects to integrate circular principles into their design methodologies, fostering a culture of sustainability that aligns with policy initiatives at both local and global levels.

2.6 Recycled Concrete as a Strategic Design Question

This segment seeks to reposition the discussion around recycled concrete from viewing it merely as an alternative to recognizing it as a strategic design choice within architectural practice.

Recycled Aggregate Concrete (RAC) is a promising, yet controversial material used by architects seeking sustainable alternatives. Despite evidence demonstrating its viability regarding strength and durability, concerns regarding material performance e, regulatory constraints, and prevailing biases often inhibit its broader acceptance (Ding et al., 2016; Zhang et al., 2020).

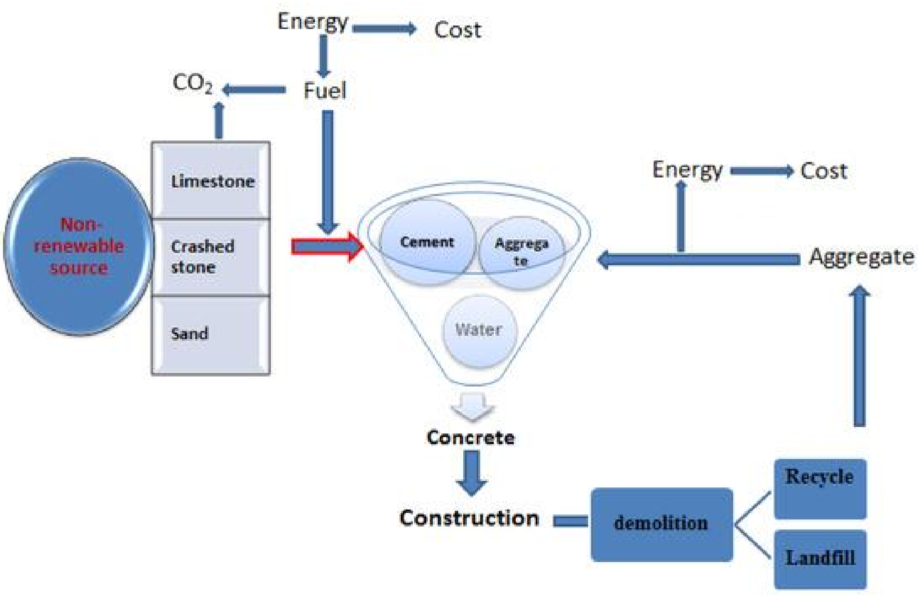


Figure 13 Material and energy flows associated with conventional concrete production and end-of-life pathways, illustrating sources of CO_2 emissions, reliance on non-renewable resources, and the role of recycling and landfilling within the concrete life cycle. (Makul et al., 2021)

Figure 13 illustrates the material and energy flows underlying conventional concrete production and its end-of-life pathways, highlighting the sources of embodied carbon embedded within the material system.

The diagram shows how nonrenewable raw materials, in particular limestone for cement production, are combined with energy intensive processes that generate significant CO2 emissions. Throughout construction activities, additional environmental burdens arise from aggregate extraction, fuel consumption, and transportation. At the end of the building life cycle, concrete is either land filled or recycled. Recycling reduces dependence on virgin aggregates and mitigates materiel-related emissions.

Within the context of this thesis, the figure explains why recycled aggregate concrete should be considered a strategic material rather than a minor alternative. In the concrete life cycle, cement production remains the dominant source of embodied CO2. However, recycled aggregate concrete reduces the need for virgin aggregate extraction and construction waste disposal.

By reducing dependence on non-renewable aggregates and diverting concrete waste from landfill, recycled aggregate concrete mitigates material-related emissions and environmental pressures associated with quarrying, processing, and transport. As such, its sustainability contribution is complementary to rather than a substitute for cement-related decarbonization strategies.

Table 1 Conceptual comparison of conventional concrete and recycled aggregate concrete across environmental, technical, and architectural dimensions.

Aspect	Conventional Concrete (NC)	Recycled Aggregate Concrete (RAC)
Aggregate source	Virgin aggregates	Recycled CDW
Embodied carbon	High	Reduced (context-dependent)
Mechanical performance	Established	Design-dependent
Durability perception	Reliable	Risk-sensitive
Architectural role	Default material	Strategic material choice

Table 1 shows a summary of the major differences between conventional concrete and recycled aggregate concrete. It clearly shows that distinctions between the two extend beyond mechanical performance to environmental and perceptual dimensions. This table shows that RAC is a strategic architectural material and not just a direct substitute to conventional concrete.

There is always the issue of perception, that the recycled concrete is inferior to new concrete which limits the potential for innovative design approaches. Architects may exhibit hesitancy in employing RAC due to fears of potential failures or client perceptions, leading to missed opportunities for environmental stewardship (Xu et al., 2018).

Addressing these misconceptions requires a concerted effort to educate practitioners on the efficacy of RAC in various applications, including structural enhancements when combined with supplementary materials (Vdovin et al., 2018). This shift in narrative—

framing RAC as a strategic decision rather than a fallback option—will foster a more proactive approach to sustainable material selection in architectural practices.

2.7 Research Gap and Positioning

The objective of this section is to clarify and articulate the unique positioning of this thesis within existing literature, particularly in relation to engineering studies on recycled concrete.

Table 2 Key technical, regulatory, and cultural barriers influencing the architectural adoption of recycled aggregate concrete and corresponding opportunities.

Category	Barrier	Opportunity
Technical	Aggregate variability	Mix optimization
Regulatory	Conservative standards	Policy evolution
Cultural	Risk perception	Education and precedent

Table 2 shows major barriers limiting the adoption of recycled aggregate concrete while identifying corresponding opportunities for reduction. This goes to the heart of the thesis demonstrating that the use of RAC is not only influenced by technical constraints. It is also influenced by regulatory frameworks and professional culture.

The existing body of literature largely emphasizes the technical aspects of recycled concrete, focusing on mechanical properties and durability indicators (Vieira & Horvath, 2008). However, this information often lacks direct relevance for architects. This leaves a significant gap between engineering research and architectural practice. This thesis aims to address this gap by exploring the implications of recycled concrete use, while encouraging and pushing for a more integrative understanding of material selection that is relevant to architects (Fleissner & Baniassad, 2007).

This research does not seek to re-invent concrete. The aim is to reinterpret its application within the architectural context. This thesis intends to enrich discussions surrounding sustainable practices in architecture and provide guidance for practitioners navigating contemporary material challenges. This is done by examining how recycled concrete can be effectively integrated into design strategies (Arora et al., 2025).

2.8 Recycled Aggregates: Classification, Microstructure, and Availability

2.8.1 Construction and Demolition Waste (CDW) as a Resource

Construction and demolition waste (CDW) represents one of the largest material flows generated by the built environment and constitutes a strategic secondary resource for reducing landfill dependency and conserving virgin aggregates. According to European assessments, mineral CDW dominates the non-hazardous waste stream, with concrete identified as the single largest fraction. The Joint Research Centre (JRC) reports that concrete accounts for approximately 56.2% of CDW (excluding excavated soil and dredging spoil), confirming its relevance as the primary feedstock for recycled aggregate production (Pacheco et al., 2023).

Table 3 Indicative composition of construction and demolition waste across selected European countries. (Pacheco & Brito, 2021)

Type of Waste	Croatia	Denmark	Estonia	Germany	Hungary	Luxemburg	Portugal	Slovakia
Concrete and ceramics	30%	56%	21%	59%	55%	69%	71%	36%
Wood, plastic and glass	1%	4%	6%	5%	1%	7%	3%	2%
Bituminous mixes	0%	0%	0%	20%	0%	0%	0%	0%
Metals	44%	15%	50%	9%	21%	11%	7%	45%
Insulating materials and materials with asbestos	2%	3%	1%	1%	6%	2%	1%	0%
Gypsum-based	0%	2%	1%	1%	5%	1%	0%	0%
Other CDW	22%	20%	21%	4%	21%	10%	17%	17%

Table 3 shows the variability in construction and demolition waste composition across selected European countries. It highlights the substantial differences in material fractions like concrete, ceramics, metals, and mixed CDW streams. Countries like Portugal, Luxembourg, and Germany concrete and ceramics dominance of values more than 60%. Other countries exhibit higher shares of metals or mixed CDW. The differences come from the use of different types of construction, demolition practices, recycling infrastructure, and national reporting methodologies. From the perspective of recycled aggregate production, such variability directly affects both the quantity and quality of available feedstock. Countries with higher proportions of concrete and ceramic waste offer more favorable conditions for producing concrete-only recycled aggregates, whereas regions with higher shares of mixed or metallic waste require more advanced sorting and processing to achieve aggregates suitable for concrete applications.

In quantitative terms, the generation of non-hazardous mineral CDW in the European Union is estimated at 322.79 million tons per year, corresponding to approximately 0.73 tons per capita. However, CDW generation rates and material composition vary significantly across countries due to differences in construction practices, demolition rates, economic cycles, and reporting methodologies.

This variability directly influences the feasibility, quality, and consistency of recycled aggregate supply chains, highlighting the importance of local context in RAC implementation.

These findings confirm that CDW availability is not a marginal phenomenon but an industrial-scale resource capable of supporting structured recycling systems, provided that appropriate sorting, processing, and quality control strategies are implemented.

Table 4 Construction and demolition waste availability and composition (EU context) (Pacheco et al., 2023)

Indicator	Reported value	Relevance to RAC
Share of concrete in CDW (excluding soil)	~56.2%	Confirms concrete as the dominant recyclable fraction
Annual non-hazardous CDW generation (EU)	~322.79 Mt	Industrial-scale feedstock availability
Per-capita CDW generation	~0.73 t/capita	Regional planning relevance
Variability among countries	High	Explains differences in RA quality and feasibility

2.8.2 Types of Recycled Aggregates: Fine and Coarse Fractions

Recycled aggregates (RA) are not all the same material. In fact, they are classified according to their particle size. This fact directly affects their suitability for concrete production. Typically, the RA are classified in two groups. Coarse recycled aggregates typically more than 4 mm in size, and fine recycled aggregates that are less than 4 mm in size. Each of these aggregates present distinct characteristics and limitations.

The most suitable fraction for use as recycled aggregate concrete is generally the coarse ones. This fact is particularly true when the coarse aggregates are derived from concrete rich CDW streams.

Their mechanical performance, although typically inferior to natural aggregates, can be controlled through selective demolition, crushing techniques, and grading optimization. Consequently, most structural RAC research and standardization efforts focus on coarse RA.

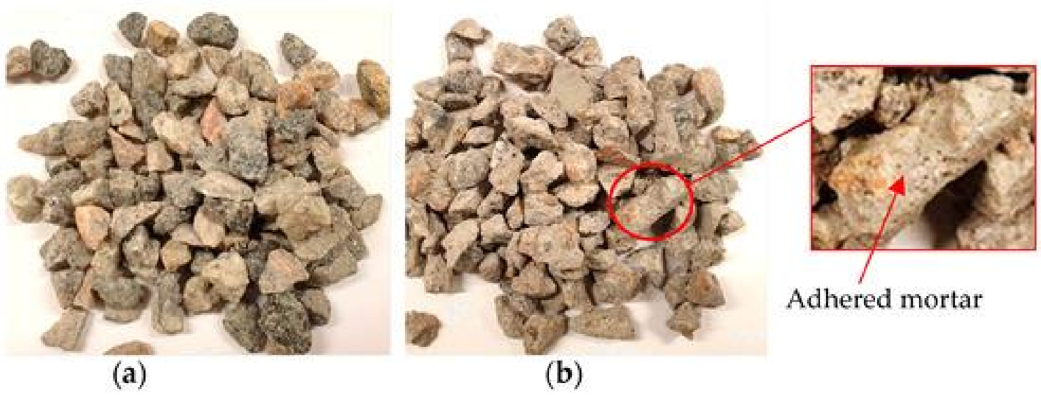


Figure 14 Coarse aggregate fractions: (a) crushed natural rock; (b) crushed concrete aggregates showing adhered mortar.(Sadagopan et al., 2023)

Figure 14 compares coarse aggregate fractions obtained from natural crushed rock and from crushed concrete elements. While crushed natural aggregates (Figure 14.a) exhibit relatively clean and dense surfaces, crushed concrete aggregates (Figure 14.b) are characterized by the presence of adhered old mortar attached to the original natural aggregate core. This adhered mortar is a defining feature of recycled concrete aggregates and is responsible for increased surface roughness, higher porosity, and greater water absorption compared to natural aggregates.

These characteristics influence the mechanical performance and durability of recycled aggregate concrete. However, this does not mean it is not used in structural applications, but appropriate processing, quality control, and mix design adaptations need to be applied. This figure clearly shows the difference between natural and recycled coarse aggregates. It also explains why coarse recycled aggregates are the best choice for RAC production.

In contrast, fine recycled aggregates present greater challenges. During crushing operations, weaker constituents and adhered mortar tend to concentrate in the fine fraction, resulting in higher porosity, higher water absorption, and increased impurity content. These characteristics negatively affect workability, strength development, and durability, which explains why many standards restrict the use of fine RA in structural concrete or limit replacement ratios (Pacheco et al., 2023; Safiuddin et al., 2013).

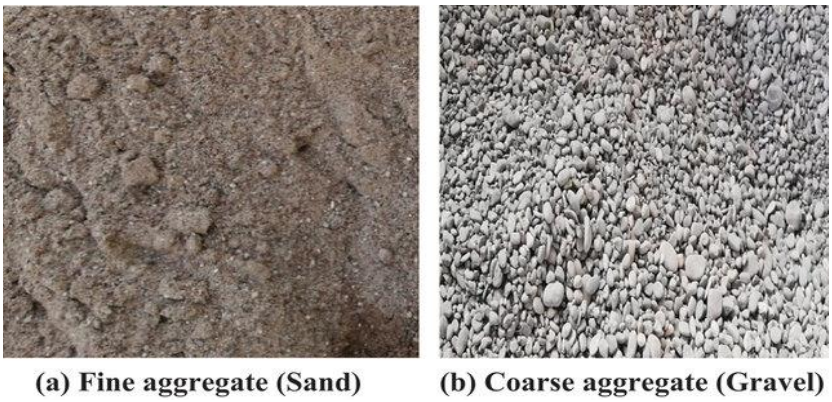


Figure 15 Comparison between fine aggregate (sand) and coarse aggregate (gravel), illustrating differences in particle size distribution, surface texture, and grading relevant to concrete mix design. (Shukur et al., 2023)

Figure 15 illustrates the fundamental distinction between fine and coarse aggregates used in concrete production. Fine aggregates (sand) consist of smaller particles that primarily fill voids between coarse aggregates and contribute to workability and packing density, while coarse aggregates (gravel) provide the primary load-bearing skeleton of concrete. This size-based distinction is critical when considering recycled aggregates, as crushing and demolition processes tend to concentrate weaker constituents and adhered mortar in the finer fractions. Consequently, fine recycled aggregates typically exhibit higher porosity and water absorption compared to coarse recycled aggregates, which explains their more limited use in structural recycled aggregate concrete and the stricter replacement limits imposed by current standards.

In Table 5, the classification of recycled aggregate concrete is ostensible by grading and application of concrete.

Table 5 Classification of recycled aggregates by grading and application

RA type	Size range	Typical applications
All-in RA	0–32 mm	Road base, backfilling
Coarse RA	>4 mm	Structural/non-structural concrete
Fine RA	≤4 mm	Limited concrete use
Variability among countries	High	Explains differences in RA quality and feasibility

2.8.3 Concrete-Only vs Mixed Recycled Aggregates

Beyond particle size, the origin and composition of recycled aggregates critically determine their performance. A fundamental distinction exists between concrete-only recycled aggregates, produced predominantly from demolished concrete structures, and mixed recycled aggregates, which include masonry, asphalt, gypsum-based materials, glass, and other construction debris.

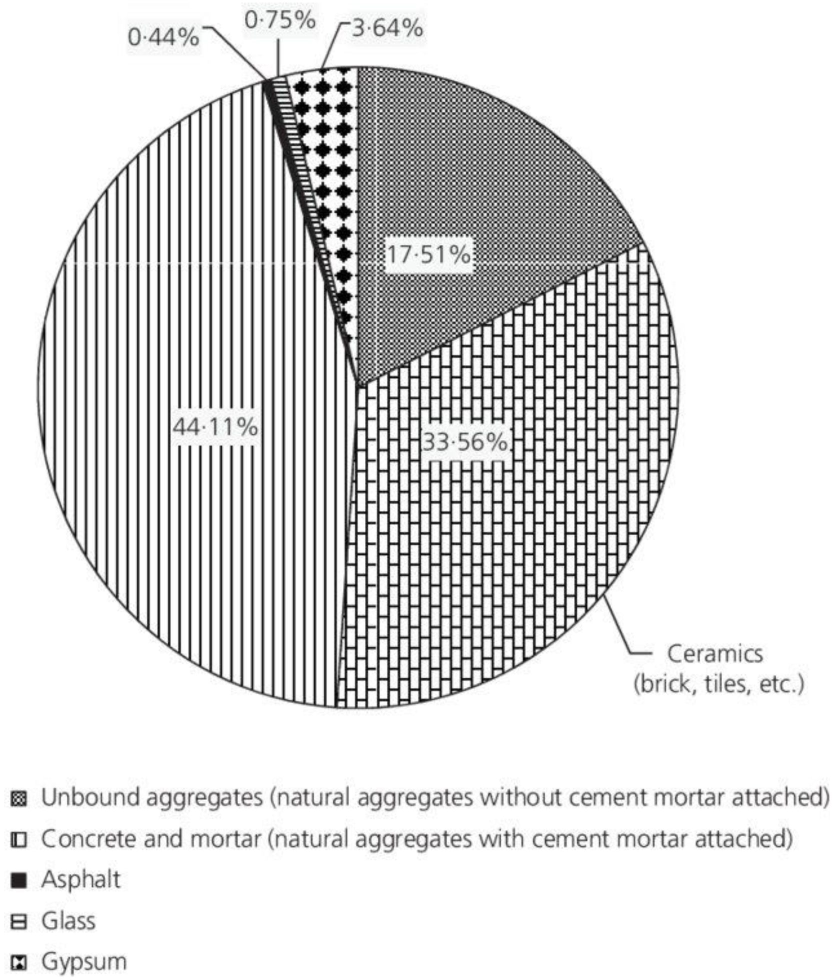


Figure 16 Typical constituent composition of recycled aggregates derived from construction and demolition waste Based on a representative data set reported by (García-González et al., 2015). The percentage refers to the studied aggregate sample and should be interpreted as indicative values rather than European average.

Figure 16 illustrates an indicative composition of mixed recycled aggregates derived from construction and demolition waste, based on the sample reported by García-González et al. (2015). The figure should not be interpreted as an average of several European countries, but as a representative example showing the heterogeneous nature of recycled aggregates.

Naturally, they contain a variety of recycled aggregates including ceramics (such as bricks and tiles), asphalt, glass, and gypsum-based material. Because they are typically more porous, weaker, or chemically reactive, the presence of these non-concrete constituents can have a direct effect on the quality of the recycled aggregates. They make them less reliable, less durable, and have an adverse effect on their mechanical performance. The figure shows that when targeting recycled aggregates for use in structural concrete, special care must be taken in selective demolition, sorting, and constituent classification.

Recycled aggregates containing only concrete, exhibit superior mechanical consistency and durability potential. Even with the presence of adhered mortar, their mineralogical composition closely resembles that of natural aggregates. On the other hand, mixed recycled aggregates contain mechanically weaker and more porous constituents. This fact affects their strength, stiffness, and durability. Recycled aggregates containing gypsum create the most problems because of their potential to cause durability issues related to sulfate.
European standards such as EN 933-11 addresses this issue of variability in composition. It classifies recycled aggregates based on constituent mass fractions, enabling objective quality control and specification. This classification provides a practical framework for limiting contaminants and tailoring recycled aggregates for concrete applications (Pacheco et al., 2023).

Table 6 EN 933-11 constituent classification of recycled aggregates

Code	Constituent	Impact on RAC
Rc	Concrete and mortar	Desired fraction (with adhered mortar effects)
Ru	Unbound natural stone	Mechanically favorable
Rb	Masonry materials	Increased porosity, lower strength
Ra	Bituminous materials	Poor bonding
Rg	Glass	Workability and bond issues
X	Other materials (gypsum, wood, plastics, etc.)	Generally deleterious

2.8.4 Interface Transition Zone (ITZ) in Recycled Aggregate Concrete

A defining microstructural characteristic of recycled aggregate systems is the presence of multiple interfacial transition zones (ITZs). While conventional concrete contains a single ITZ between natural aggregate and cement paste, recycled aggregates typically consist of a natural aggregate core coated with adhered old mortar. This results in an old ITZ (natural aggregate–old mortar) and a new ITZ (recycled particle–new cement paste).

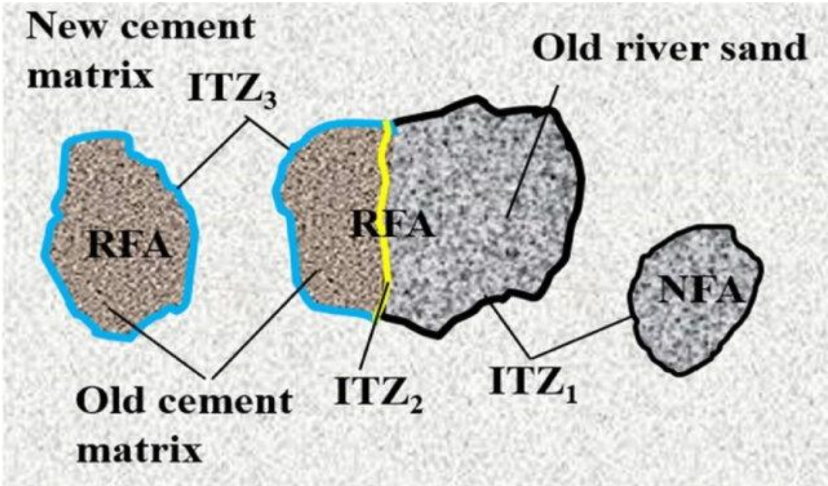


Figure 17 Schematic representation of interfacial transition zones (ITZs) in recycled aggregate concrete, illustrating the presence of an old ITZ between the original natural aggregate and adhered old mortar, and a new ITZ between the recycled aggregate particle and the new cement matrix, in comparison with the single ITZ present in natural aggregate concrete. (Z. Xu et al., 2021)

In figure 17, RFA denotes Recycled Fine Aggregate, while NFA denotes Natural Fine Aggregate.

Figure 17 schematically illustrates the microstructural configuration of recycled aggregate concrete in comparison with conventional concrete, highlighting the presence of multiple interfacial transition zones (ITZs). In natural aggregate concrete, a single ITZ (ITZ_1) exists between the natural aggregate (NA) and the newly formed cementitious matrix.

In recycled aggregate concrete, recycled particles have a natural aggregate core but it usually is fully or partially coated with old cement mortar. This gives rise to additional interfacial regions and as a result three distinct ITZs can be identified:

1) the ITZ between the natural aggregate and the new cement material (ITZ_1) similar to that in conventional concrete.
2) the ITZ between the natural aggregate and the old residual cement from the parent concrete (ITZ_2).
3) the ITZ between the old adhered mortar and the new cement formed during the production of aggregate concrete (ITZ_3).
The presence of these different interface configurations is what differentiates the recycled aggregate concrete from conventional concrete. It also has a major influence on the physical and mechanical behavior of recycled aggregates. The old residual mortar is more porous and micro cracked than natural aggregate. This leads to more water absorption

and reduced stiffness of the recycled particle. Due to differences in hydration history, chemical composition, and surface characteristics, ITZ between old and new mortar often exhibits weaker bonding characteristics. This also makes the recycled aggregate concrete more permeable, allows enhanced transport of aggressive agents, and becomes more sensitive to curing. The existence of multiple ITZ should not be looked at as a limitation of recycled aggregate concrete. In fact, the presence of multiple ITZs dictates the need to address different parameters while working the recycled aggregate concrete. These parameters include engineering strategies such as selective demolition to limit contaminants, processing techniques to control adhered mortar content, and optimized mix designs to incorporate different cement materials. In this context, the existence of multiple ITZ structures actually provides a scientific basis for improving recycled aggregate concrete performance. This is an advantage rather than a justification for excluding recycled aggregates from structural applications.

The multiple ITZ structure provides a scientific explanation for the limitations of recycled aggregates. These limitations include higher porosity, increased water absorption, reduced stiffness, and enhanced permeability. These characteristics have a direct effect on mechanical performance and durability especially in aggressive environments.

From a design perspective, ITZ-related weaknesses highlight the importance of selective demolition, aggregate processing, and mix-design strategies rather than constituting a fundamental barrier to RAC adoption.
The material characteristics discussed in this section form the basis for evaluating the mechanical, durability, and environmental performance of recycled aggregate concrete, which is explored in detail in Chapter 3.

3 Literature Review

This chapter provides a literature review focusing on conventional concrete, recycled aggregate concrete (RAC), its mechanical properties, durability, environmental performance, regulatory frameworks, and barriers to its adoption. A thorough understanding of these topics is essential for positioning recycled aggregate concrete as a viable alternative in sustainable architecture.

3.1 Conventional Concrete: Composition & Impacts

3.1.1 Composition of Conventional Concrete

Conventional concrete is a composite material primarily composed of Portland cement, natural aggregates (both fine and coarse), and water. The cement serves as the binder, while natural aggregates contribute to the concrete's mechanical strength and stability. The standard mix ratio commonly used is approximately 1 part cement, 2 parts sand (fine aggregate), and 4 parts gravel or crushed stone (coarse aggregate) (Bravo, Silva, et al., 2015). Supplementary cementitious materials, such as fly ash, silica fume, and chemical admixtures, may also be included to enhance specific properties like workability and durability.

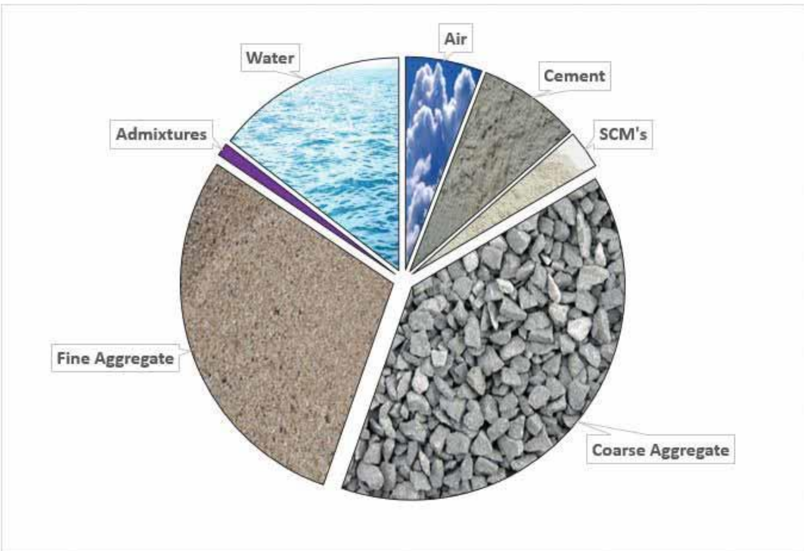


Figure 18 Typical composition of conventional concrete showing the relative proportions of cement, fine aggregates, coarse aggregates, water, and admixtures. (*Cement and concrete, still outperforming in the sustainability era*, 2019)

Figure 18 illustrates the basic material composition of conventional concrete, highlighting the dominance of aggregates by volume and the critical binding role of cement. While aggregates constitute the majority of the material mass, cement is responsible for most of the embodied carbon associated with concrete. This distinction underlines why sustainability strategies often focus on reducing cement content while simultaneously addressing aggregate sourcing through recycled alternatives.

3.1.2 Environmental Impacts

The environmental impacts associated with conventional concrete are substantial. Cement production accounts for approximately 6-8% of global carbon dioxide emissions, primarily due to the high temperatures required in the calcination process of raw materials and decomposition of limestone to produce clinker (IRENA & UN Climate Change High-Level Champions 2023) .

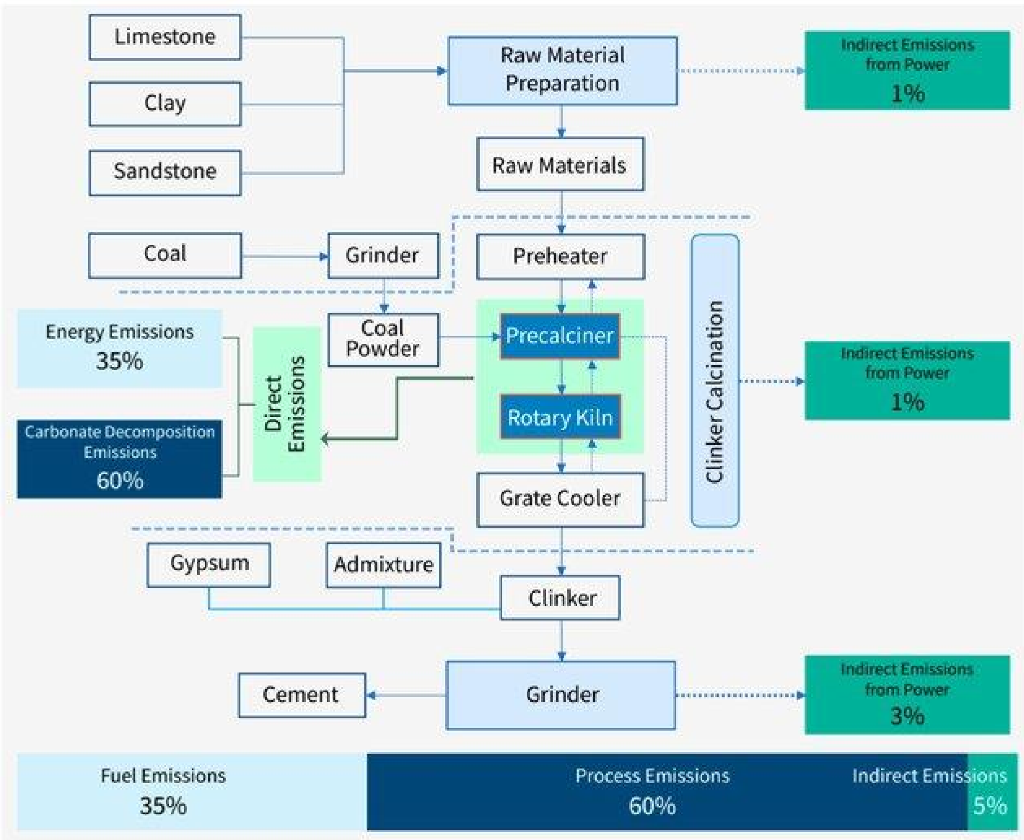


Figure 19 Cement manufacturing process with associated CO_2 emission sources, illustrating the relative contribution of process emissions from limestone calcination, fuel combustion emissions, and indirect emissions from electricity use.(Shin et al., 2025)

Figure 19

provides a detailed breakdown of the cement manufacturing process and highlights the origin of carbon dioxide emissions across different production stages. The diagram shows that 60% of emissions come from the chemical decomposition of limestone during clinker calcination which is a fundamental process in cement production. 35% of emissions come from fuel combustion to get the kiln temperature to more than 1400 C. A smaller fraction of about 5% comes from indirect emissions from electricity consumption. What this data shows is that the largest share of emission comes from the calcination process itself. That means that concentrating the efforts on reducing energy consumption alone cannot eliminate most emissions from cement production because most of the emissions come from the calcination process. This also means that in order to reduce emissions there must be a material-based strategies. These strategies include lowering clinker replacing natural aggregates with recycled aggregates.

To contextualize cement-related emissions within the global carbon budget, it is useful to compare them with other major sources of anthropogenic CO_2 emissions, as shown in Figure 20

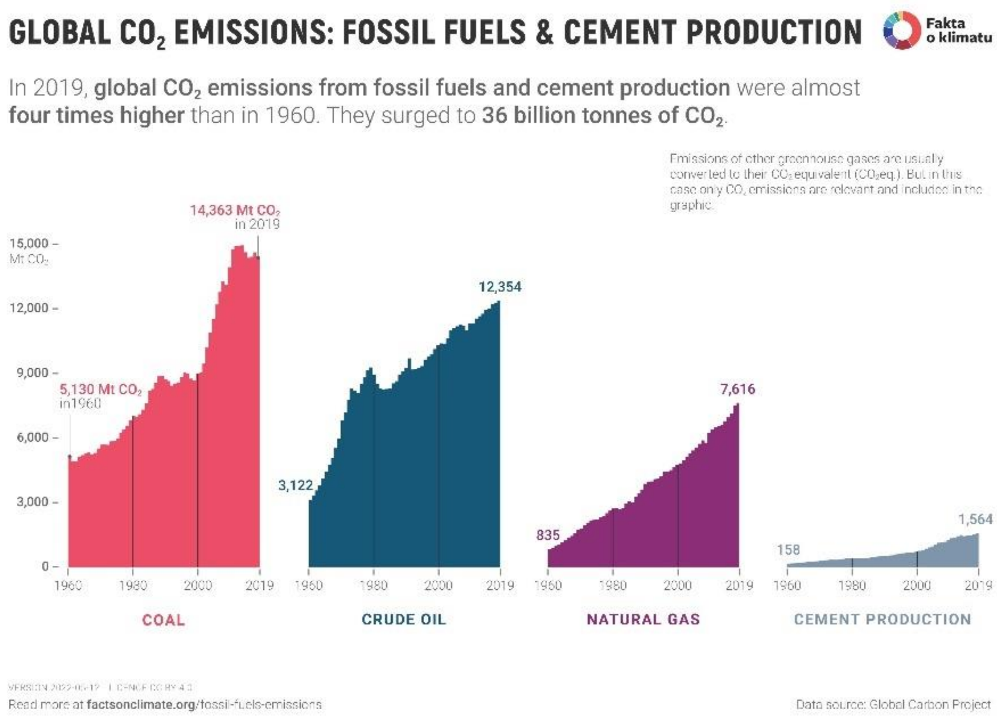


Figure 20 Global CO_2 emissions from fossil fuels and cement production between 1960 and 2019, illustrating the relative contribution of coal, crude oil, natural gas, and cement production. Source: Global Carbon Project, visualized by Fakta o Klimatu.

Figure 20 puts the CO_2 emissions of cement in comparison to global emissions landscape dominated by fossil fuel combustion. The figure shows that cement production is responsible for a smaller share of global CO_2 emissions compared to coal, oil, and natural gas. However, the emissions from the production of cement have increased steadily over the years and are distinct in nature. A big proportion of cement emissions come from the chemical decomposition of limestone during clinker production. As such these emissions cannot be limited or reduced through fuel substitution alone unlike energy related emissions. This fact highlights the need for different strategies especially in the construction sector. These strategies include material selection, reduction in cement demand, improved material efficiency, and the use of recycled aggregates to complement the reduction of energy related emissions Additionally, the extraction of natural aggregates can lead to habitat destruction, soil erosion, and loss of biodiversity (Su et al., 2015). These environmental challenges underscore the urgent need to explore more sustainable alternatives in concrete production.

3.2 Recycled Aggregate Concrete: Definition & Development

3.2.1 Definition of Recycled Aggregate Concrete

Recycled Aggregate Concrete (RAC) is defined as concrete incorporating recycled aggregates derived from construction and demolition waste. These aggregates are typically produced by crushing and processing old concrete structures, providing an ecologically sustainable alternative to natural aggregates (Silva et al., 2016). The main objective in the use of recycled aggregates is to minimize landfill waste and conserve natural resources. Figure21 shows a clearer comparison between linear or natural concrete and circular or recycled concrete productions pathways. It examines the material flows connecting demolition, recycling and new concrete production.

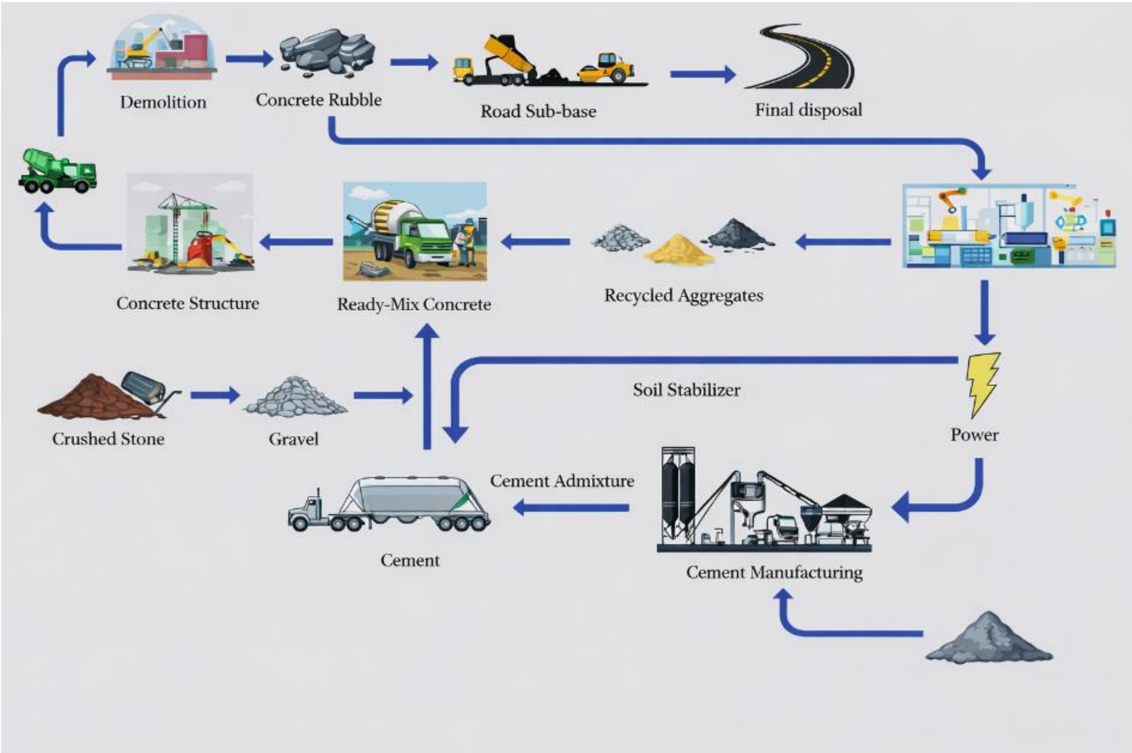


Figure 20 Integrated material flow of conventional and recycled aggregate concrete, illustrating demolition pathways, recycled aggregate processing, concrete production, and end-of-life options within a circular construction system. (S C et al., 2022)

Figure 21 presents an integrated overview of material flows associated with both conventional concrete production and recycled aggregate concrete within a circular construction system. The diagram illustrates how concrete structures, at the end of their service life, undergo demolition and generate concrete rubble that can either be disposed of or processed into recycled aggregates

These recycled aggregates partially replace conventional aggregates such as crushed stone and gravel, by adding them into ready mix concrete production. The figure also shows that while the use of recycled aggregates reduces impacts associated with aggregate extraction and disposal, emissions related to the production of cement still requires energy and remains largely unchanged.

The figure shows a comparison between two ways to use concrete Linear and Circular. Linear model is making the concrete, using the concrete, demolish it, and finally dispose of it through. Circular model is making concrete, use it, demolish it, recycle it, and use it again. In the Linear model, current practices crush old concrete and use it for low value applications, such as road foundations, instead of up cycling it and using it in construction. In circular model, instead of letting the concrete go to waste, the aggregates are recovered and recycled in the production of new structural concrete. The use of recycled aggregate concrete provides many benefits at different stages of the concrete life cycle. The benefits include reducing demand for new aggregates, re-using construction and demolition waste instead of land filling, and improving resource efficiency in sustainable construction

3.2.2 Development and Historical Context

The concept of RAC has evolved significantly in recent decades, gaining attraction as a sustainable construction material. Early research focused on the mechanical properties of RAC, examining the trade-offs between using recycled versus natural aggregates (Sadrmomtazi et al., 2016). Recent studies explore advanced formulations and methodologies to enhance the performance of RAC, addressing earlier misconceptions regarding its perceived inferior quality relative to conventional concrete (Wang et al., 2019). This shift reflects a growing recognition of the need for sustainable construction practices in response to escalating resource shortages and environmental concerns (Pedro et al., 2019).

Table 7 Historical development of recycled aggregate concrete (RAC) and its evolving role in construction practice.

Period	Geographic Context	Primary Drivers	Typical Applications	Key Developments and Limitations
1940s–1950s	Europe	Post-war reconstruction, material scarcity	Road bases, low-strength concrete	Large volumes of war debris reused pragmatically; limited processing; no performance standards
1970s	United States	Landfill pressure, resource conservation	Non-structural elements, fill materials	Reintroduction of RCA primarily in low-risk applications; minimal structural acceptance
1990s–2000s	Europe, Japan	Environmental regulation, research funding	Pilot structural elements	Systematic investigation of mechanical and durability properties; early mix design optimization
2010s–present	European Union	Circular economy policy, climate mitigation	Structural and non-structural concrete	Standardization efforts (e.g., EN 206), improved processing technologies, and partial replacement strategies

Table 7 traces the historical evolution of recycled aggregate concrete from an emergency-driven reuse strategy to a material system increasingly embedded within sustainability and circular economy frameworks. Early applications in post-war Europe were motivated by urgent reconstruction needs and material shortages, resulting in largely unregulated and performance-agnostic reuse of demolition debris.

Once the urgency went down, the interest in recycled aggregates declined. In the 1970, renewed environmental concerns prompted the re use of recycled aggregates in non-structural applications especially in the United States.
From the 1990 onward, the production of RAC became more systematic driven by scientific research and regulatory attention in Europe and Japan. Research concentrated on understanding the mechanical and durability implications of recycled aggregates. The main goal was to challenge the perception that recycled aggregate concrete was an inferior product. Recently, the importance of using RAC has come to light due to many factors including, European circular economy objectives, advances in aggregate processing technologies, improved quality control, and evolving standards that allow some controlled use in structural concrete. This historical development shows that the adoption of recycled aggregate concrete has depended not only on its technical performance, but also on regulations, public perception, and industry practices. These factors continue to influence its performance requirements, regulatory acceptance and practical implementation.

3.3 Mechanical Performance of RAC

3.3.1 Overview of Mechanical Properties

Mechanical performance is a crucial criterion in assessing the viability of RAC. Research consistently indicates that RAC often exhibits lower compressive strength compared to conventional concrete, with strength reductions typically ranging from 20% to 40% depending on several factors, including the source and quality of recycled aggregates used (Tošić et al., 2020). However, numerous studies also show that under certain conditions, such as optimal mix designs and the inclusion of fibers, the performance of RAC can be improved, making it more competitive against traditional concrete (Makul et al., 2021).

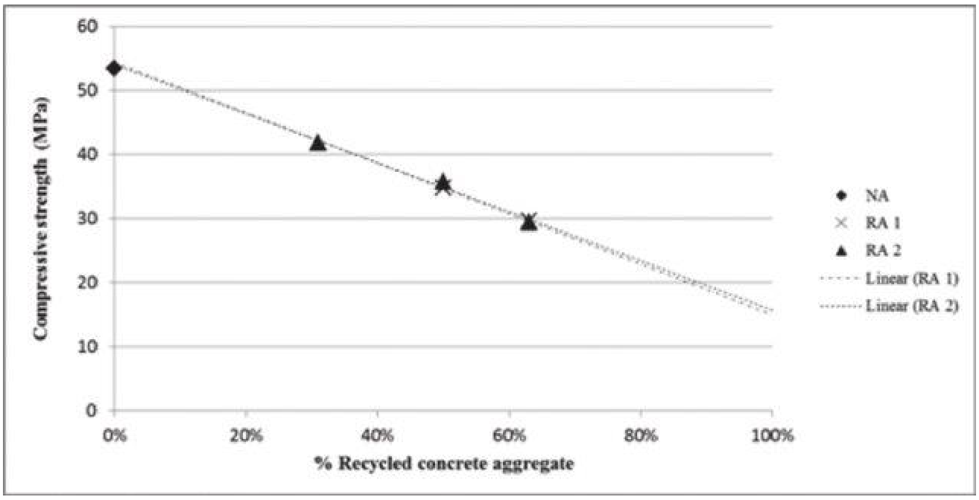


Figure 21 Relationship between recycled concrete aggregate content and compressive strength of concrete, illustrating the reduction in strength with increasing recycled aggregate replacement ratios. Data points correspond to natural aggregate concrete (NA), and recycled aggregate concretes (RA1 and RA2), with linear trendlines shown for comparison.(Pavlů et al., 2014)

Figure 22 shows the relationship between recycled concrete aggregate content and compressive strength. From the figure it is clear that compressive strength goes down as the percentage of recycled aggregates go up. At high percentage of recycled aggregate concrete, the compressive strength decreases significantly. This is due to the presence of adhered mortar on recycled aggregates, which increases porosity, reduces stiffness, and weakens the ITZ (interfacial transition zone) between aggregate and cement paste.

Using two different recycled aggregates (RA1 and RA2) gave different results in compressive strength. This shows that RAC performance is directly related to the source and quality of the aggregate which significantly influences mechanical outcome. Despite the results shown in Figure 22, the data also suggest that partial replacement levels—typically below 40–50%—can retain compressive strengths within ranges suitable for many structural and non-structural applications when appropriate mix

design strategies are employed. This observation supports the broader conclusion in the literature that mechanical performance limitations of RAC are not absolute, but conditional, reinforcing the importance of controlled replacement ratios and material characterization in both architectural and engineering applications.
To better contextualize the observed strength reductions, it is important to briefly outline the mix design framework adopted in the experimental program from which Figure 22 is derived. In the study by Pavlů et al. (2014), all concrete mixes were designed with a constant effective water–cement ratio (w/c_eff = 0.50) in order to isolate the influence of recycled aggregate replacement on mechanical performance. Natural aggregates were progressively replaced by recycled concrete aggregates at replacement ratios of up to 63% of the total aggregate content, corresponding to full substitution of the coarse aggregate fraction (4–16 mm).

The recycled aggregates (RA1 and RA2) came from a waste recycling plant. They consisted mainly of crushed concrete (95-96%), with small amounts of masonry and asphalt. Due to the fact that the recycled aggregates have a higher water absorption capacity than natural concrete, additional water was added to maintain same water to cement ratio in all mixtures. No extra cement was added.
Under these controlled conditions, figure 22 shows a decrease in compressive strength. This can be explained by the properties of the recycled aggregates, including adhered mortar content, increased porosity, and reduced aggregate stiffness, rather than differences in cement content or curing conditions. These results clearly show that aggregate quality and replacement ratio affect the compressive strength of the recycled aggregate concrete.

As illustrated in Figure 23, the disparity in compressive strength between RAC and conventional concrete diminishes with curing age, supporting the view that long-term performance may approach that of conventional mixes under optimized conditions.

The experimental program included six concrete mixtures with recycled aggregate substitution rates of 0%, 20%, 40%, 60%, 80%, and 100%, tested after 3, 7, and 28 days of curing.

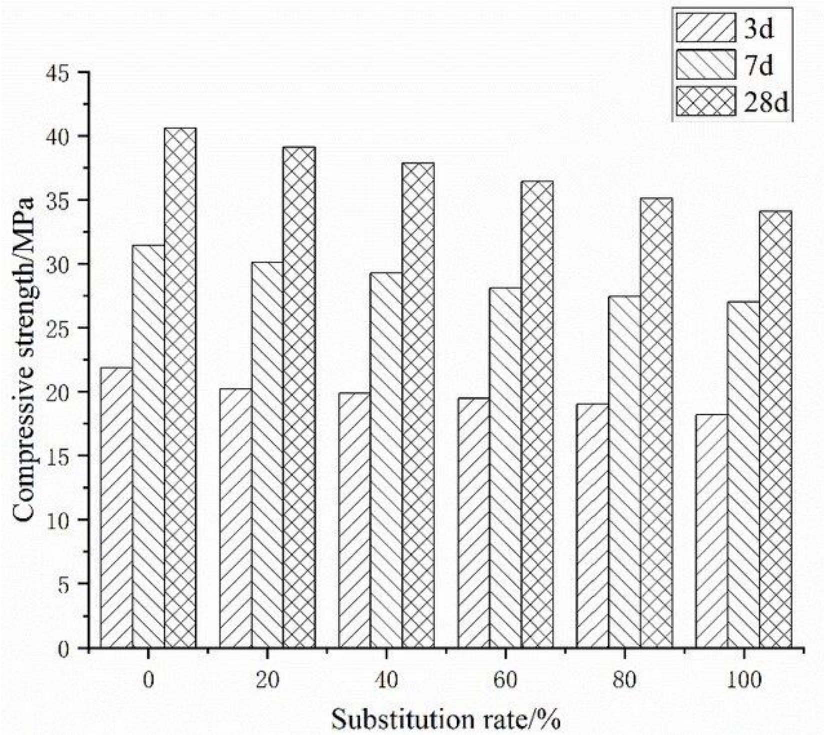


Figure 22 Compressive strength development of recycled aggregate concrete at different substitution rates and curing ages (3, 7, and 28 days), showing the influence of recycled aggregate content on early-age and long-term strength.(Li et al., 2021)

Figure 23 presents the evolution of compressive strength in recycled aggregate concrete as a function of both recycled aggregate substitution rate and curing age. The results demonstrate that compressive strength increases significantly with curing time for all substitution levels, confirming the continued hydration and densification of the cementitious matrix.

At early curing ages (3 and 7 days), higher recycled aggregate replacement levels result in lower compressive strength because recycled aggregates have higher porosity and weaker interfacial transition zones.

By 28 days, the difference in compressive strength between low and high replacement levels become smaller. This indicates that longer curing improves the performance of recycled aggregate concrete and partially offsets its lower early age strength.

The improved performance at later ages is commonly attributed to enhanced bonding between the cement paste and recycled aggregates, as well as the potential pozzolanic activity of residual cementitious materials attached to the recycled aggregates.

From a practical construction perspective, however, reliance on prolonged or ideal curing conditions represents a significant limitation.

While under laboratory conditions it is feasible to do controlled curing for 28 days or longer, this cannot be done on real construction sites due to economic, scheduling, and logistical constraints. That means that curing for long periods of times cannot be universally applicable in order to get the desired compressive strength from the recycled aggregate concrete when used at high rates.

That is why, in order to use replacement rates of more than 30% of the recycled aggregate concrete, additional mechanical enhancing strategies must be studied. Some of these strategies include mix design optimization, the use of supplementary cementitious materials, aggregate pretreatment techniques, or structural design adaptations. Of course, these strategies have to economically compete with conventional concrete production otherwise they are not use-able in real life.

Because everything begins and ends with economics, and because any solution has to be economically feasible otherwise it will not work, there is a need to evaluate RAC performance within the economic and operational realities of contemporary construction practice.

3.3.2 Influential Factors

Factors influencing RAC performance include aggregate quality, replacement ratios, and mix design. The specific gravity and water absorption rates of recycled aggregates contribute to the reduction in mechanical strength experienced by RAC (Bravo-German et al., 2021). Additionally, incorporating supplementary cementitious materials like fly ash or slag can enhance performance by leveraging their pozzolanic properties (Cao et al., 2023). Investigations reveal that appropriate treatment and selection of recycled coarse aggregates can lead to noticeable improvements in both tensile and compressive strengths, making them more favorable for structural applications (Pacheco et al., 2019).

Table 8 synthesizes the principal factors identified in literature as influencing the mechanical performance of recycled aggregate concrete. Rather than treating RAC performance as an inherent material limitation, the table highlights that many mechanical shortcomings are strongly dependent on controllable parameters such as aggregate quality, replacement ratio, and mix design strategy.

Although several studies have reported improved performance using aggregate pretreatment methods, it is important to distinguish between laboratory techniques and methods that can be applied in industrial production. Advanced treatments, such as thermal processing, acid washing, and extensive removal of adhered mortar, can improve recycled aggregate quality. However, these methods often require more energy, additional processing, and higher costs, making them impractical for large-scale concrete production.
More practical approaches include selective demolition, basic mechanical processing, mix design optimization, and the use of supplementary cementitious materials. These methods are more suitable for current concrete production and can improve the performance of recycled aggregate concrete on an industrial scale. Overall, the table shows that the mechanical performance of recycled aggregate concrete can be improved through appropriate aggregate selection, mix design, and production methods while remaining consistent with practical and economic constraints.

Table 8 Key factors influencing the mechanical performance of recycled aggregate concrete

Factor	Description	Effect on Mechanical Performance	Design / Specification Implication
Recycled aggregate quality	Depends on the parent's concrete strength, adhered mortar content, and crushing method	Poor-quality aggregates increase porosity and reduce compressive and tensile strength	The selection of high-quality source concrete improves RAC performance
Replacement ratio (%)	Proportion of recycled aggregate replacing natural aggregate	Higher replacement ratios generally lead to strength reduction	Partial replacement (30–50%) often balances performance and sustainability
Water absorption of aggregates	Recycled aggregates typically exhibit higher water absorption	Excessive absorption reduces effective water–cement ratio control	Pre-saturation or mix water adjustment is required
Interfacial Transition Zone (ITZ)	Weaker bond between recycled aggregate and new cement paste	Reduces load transfer efficiency and compressive strength	Use of SCMs and optimized mix design improves ITZ quality
Supplementary Cementitious Materials (SCMs)	Fly ash, slag, silica fume, etc.	Enhance later-age strength and durability through pozzolanic reactions	SCM incorporation mitigates strength loss in RAC
Aggregate treatment methods	Mechanical, chemical, or thermal treatment of recycled aggregates	Improves aggregate surface quality and bonding	Treated aggregates enable higher replacement levels
Curing conditions	Duration and quality of curing	Longer curing improves strength development in RAC	Extended curing is especially important for high RAC content mixes

3.3.3 Comparative Analysis with Conventional Concrete

Comparative Analysis with Conventional Concrete A comparative analysis of RAC and conventional concrete reveals that while RAC typically has lower mechanical performance, its differences may diminish as the material cures. Studies suggest that the mechanical properties of RAC can continue to improve over time, potentially leading to equalization of performance metrics between RAC and conventional concrete under specific conditions (Sharma, 2020).

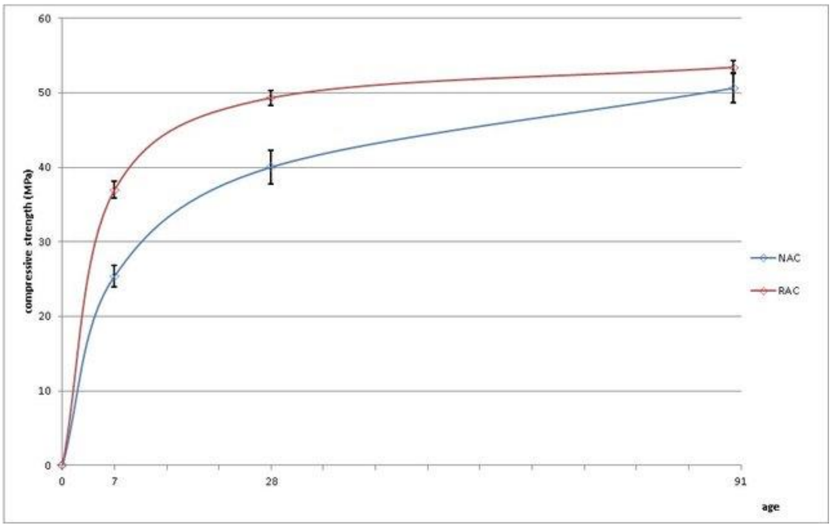


Figure 23 Compressive strength development of conventional concrete (NAC) and recycled aggregate concrete (RAC) as a function of curing age.(Lotfi et al., 2014)

Figure 24 shows an illustration comparing compressive strength development for conventional concrete (NAC) and recycled aggregate concrete (RAC) over an extended curing period. The figure shows that the rate of compressive strength of RAC increases significantly with curing time. In particular, the divergence between NAC and RAC observed at early stages gradually narrows as hydration progresses, with RAC showing substantial long-term strength development. This behavior can be attributed to continued cement hydration due to the progressive release of water entrapped in pores (the so-called internal curing effect) and progressive densification of the microstructure, as well as improved bonding within the interfacial transition zones of recycled aggregates. The results illustrated in Figure 24 support findings in the literature indicating that mechanical performance differences between RAC and conventional concrete are time-dependent rather than absolute.

To ensure a meaningful interpretation of the time-dependent strength development shown in Figure 24, it is necessary to briefly clarify the mix design conditions under which the compared concretes were produced.

The data shown in Figure 24 are based on the experimental study by Lotfi et al. (2014). In that study, recycled aggregate concrete (RAC) and natural aggregate concrete (NAC) were produced with the same cement content and similar workability, allowing the effect of aggregate type to be evaluated. Both mixtures contained CEM I 42.5R cement at a dosage of 380 kg/ cubic meter. In the RAC mixture, coarse recycled aggregates (4-16 mm) completely replaced natural coarse aggregates, while natural river gravel was used in the NAC mixture.

Because recycled aggregates absorb more water (about 5.4%) than natural aggregates (about 1.8%), additional mixing water was added to the RAC mixture to achieve similar workability. The cement content was kept unchanged, and all specimens were cured according to EN 12390-2.

Under these controlled mix design parameters, the observed convergence in compressive strength between RAC and NAC at later ages can be attributed primarily to microstructural evolution, including continued hydration, densification of the interfacial transition zone, and improved paste–aggregate bonding, rather than to differences in binder dosage or curing regime. This reinforces the interpretation that long-term mechanical performance differences between RAC and conventional concrete are time-dependent and mix-design sensitive, rather than intrinsic limitations of recycled aggregates

Consequently, while long-term curing performance provides valuable insight into the intrinsic mechanical potential of recycled aggregate concrete, its relevance for real construction practice must be interpreted with caution.

In laboratory conditions, longer curing periods can reduce the lower early-age strength of recycled aggregate concrete. However, extending the curing period is often impractical in real construction time, labor costs, and scheduling demands. In practice, structural concrete is expected to meet the required performance within the standard curing period, typically 28 days, without relying on prolonged curing. Therefore, achieving higher recycled aggregate replacement ratios in RAC cannot realistically depend on extended curing alone. Instead, performance improvements must be pursued through strategies compatible with current construction practices and cost structures, such as optimized mix design, controlled aggregate quality, appropriate use of supplementary cementitious materials, and rational limitation of replacement ratios. In this context, long-term curing results should be understood as an indicator of *material potential* rather than a directly transferable solution, reinforcing the need for practical, cost-effective design strategies when specifying RAC in architectural and structural applications.

Table 9 Comparative mechanical performance of conventional concrete (NC) and recycled aggregate concrete (RAC)

Parameter	Conventional Concrete (NC)	Recycled Aggregate Concrete (RAC)	Comparative Observation
Early-age compressive strength (≤7 days)	Higher	Lower	RAC is affected by higher porosity and weaker interfacial transition zones
28-day compressive strength	Reference value	Typically 10–40% lower	The difference is strongly dependent on the aggregate replacement ratio and quality
Long-term strength (≥56 days)	Stable	Continue to increase	The strength gap may be reduced with extended curing time
Tensile strength	Higher	Slightly reduced	Governed by recycled aggregate quality and ITZ integrity
Elastic modulus	Higher	Lower	Reduced stiffness due to aggregate heterogeneity
Sensitivity to curing conditions	Moderate	High	Extended curing significantly benefits RAC performance
Curing conditions	Duration and quality of curing	Longer curing improves strength development in RAC	Extended curing is especially important for high RAC content mixes

Table 9 provides a consolidated comparison of the mechanical performance characteristics of conventional concrete and recycled aggregate concrete, highlighting both initial limitations and long-term potential of RAC. Compared with conventional concrete, recycled aggregate concrete generally has lower early-age strength and stiffness. However, its mechanical properties improve with curing time. Long-term curing can reduce the difference in compressive strength, especially when high-quality recycled aggregates and optimized mix designs are used. The table shows that the performance difference between conventional and recycled aggregate concrete changes with curing age rather than remaining constant.

From an architectural and design perspective, this highlights the limitations of relying on extended curing strategies in practice and instead points to the need for evolution in standards and regulatory frameworks that account for the time-dependent performance characteristics of recycled aggregate concrete, allowing its safe specification based on performance-based criteria rather than fixed 28-day benchmarks alone.

3.4 Durability Performance of RAC

3.4.1 Importance of Durability

Durability is a critical aspect determining the longevity and serviceability of concrete structures. It encompasses various performance metrics, including resistance to chemical attacks (carbonation, sulphate penetration…), freeze-thaw cycles, and other environmental factors. The evaluation of RAC's durability features the complex interplay between the quality of recycled aggregates and the resultant performance of the concrete mix (Richardson et al., 2016).

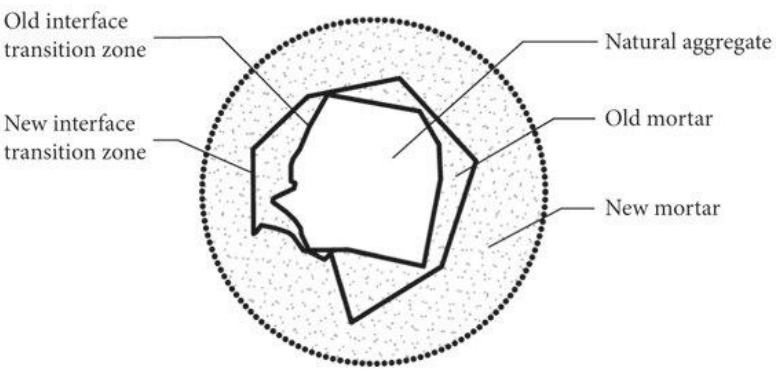


Figure 24 Schematic representation of the interfacial transition zones in recycled aggregate concrete, illustrating old and new mortar interfaces. (F. Xu et al., 2021)

Figure 25 illustrates the multi-ITZ configuration characteristic of recycled aggregate concrete, building on the interfacial transition zone mechanisms discussed earlier. The presence of old and new ITZs increases microstructural heterogeneity and porosity, which directly influences moisture transport and the ingress of aggressive agents. As a consequence, durability-related phenomena such as carbonation, chloride penetration, and freeze–thaw damage become more sensitive to aggregate quality and mix design in RAC. The figure therefore reinforces why durability, rather than strength alone, is a critical performance criterion when specifying recycled aggregate concrete under environmental exposure conditions.

3.4.2 Findings on Durability

Research demonstrates that RAC can exhibit durable characteristics comparable to conventional concrete when properly designed. In durability studies, RAC has shown effective resistance to chemical agents such as sulfates and chloride ingress (Bu et al., 2021; Guedes et al., 2013). Some studies indicate that RAC can maintain its mechanical integrity under repetitive freeze-thaw cycles, provided that quality control measures are implemented to enhance its pore structure (Zhang et al., 2021).

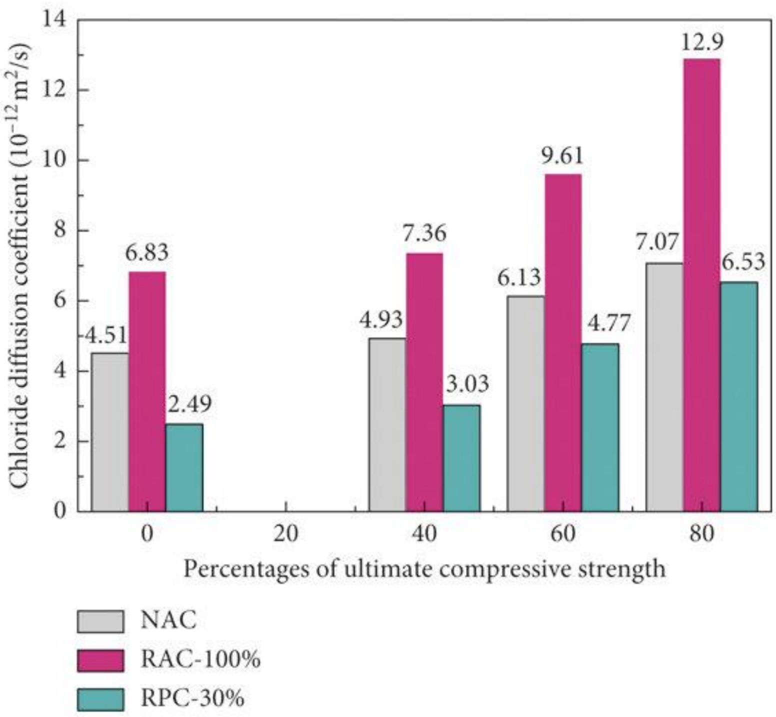


Figure 25 Chloride diffusion coefficients of conventional concrete (NAC), recycled aggregate concrete with 100% recycled aggregates (RAC-100%), and recycled powder concrete (RPC-30%) (Ma et al., 2019)

Figure 26 compares chloride diffusion coefficients for conventional concrete (NAC), recycled aggregate concrete with full aggregate replacement (RAC-100%), and recycled powder concrete (RPC-30%), where 30% of the binder is replaced by recycled concrete powder (RCP).

The results show that RAC-100% has a higher chloride diffusion coefficient than NAC at all strength levels. This is mainly due to the adhered mortar, higher water absorption of recycled aggregates, and a more porous interfacial transition zone. In contrast, RPC-30% shows much lower chloride diffusion and, in several cases, performs similarly to NAC. This improvement is attributed to the filler effect and the pozzolanic activity of recycled concrete powder, which refine the pore structure and densify the paste-aggregate interface. Overall, the figure confirms that chloride resistance in recycled-concrete systems is strongly dependent on the type and replacement strategy of recycled constituents: full aggregate substitution tends to penalize transport properties, while partial binder replacement with recycled powder can mitigate chemical ingress risks, supporting the feasibility of recycled solutions in reinforced concrete when mix design is properly engineered.

To ensure a meaningful comparison of chloride diffusion behavior among NAC, RAC, and RPC in the above figure, the concretes were prepared under strictly controlled mix-design conditions.

Following the methodologies outlined by Ma et al. (2019), the concrete mixtures were developed under stringent design protocols, maintaining a uniform 0.5 water-to-binder ratio. Target workability was standardized at a slump of 90 +/- 5 mm via precise dosing of polycarboxylate-based superplasticizer. For the RAC mixtures, recycled aggregates replaced up to 100% of the natural coarse aggregates by mass, while the cement content remained unchanged. Because recycled aggregates absorb more water, extra mixing water was added only to compensate for this, keeping the effective water-cement ratio uniform across all mixes. In RPC mixtures, recycled concrete powder replaced cement at levels up to 30% by mass, while keeping the same aggregate skeleton and curing conditions. Before undergoing chloride diffusion testing, all specimens were cured at 20 +/- 2 C and roughly 95% relative humidity. Because these conditions were strictly controlled, the differences in chloride diffusion coefficients shown in Figure26 are primarily due to the nature of the recycled materials. Specifically, this relates to the higher porosity and multi-ITZ effects in RAC-100%, and the pore refinement and micro-filter effects in RPC-30%, rather than any changes in binder content, workability, or curing methods.

Table 10 Comparison of key durability indicators for conventional concrete and recycled aggregate concrete

Durability Indicator	Conventional Concrete	Recycled Aggregate Concrete	Key Observation
Chloride ingress	Low	Moderate	Influenced by aggregate porosity and ITZ quality
Sulfate resistance	High	Comparable	Strongly dependent on cement chemistry
Carbonation depth	Lower	Slightly higher	Affected by multiple interfacial zones
Water absorption	Lower	Higher	Adhered mortar increases porosity
Long-term durability	Stable	Comparable with optimization	Mix design and curing are critical
Sensitivity to curing conditions	Moderate	High	Extended curing significantly benefits RAC performance
Curing conditions	Duration and quality of curing	Longer curing improves strength development in RAC	Extended curing is especially important for high RAC content mixes

Table 10 provides a synthesized comparison of durability-related performance indicators for conventional concrete and recycled aggregate concrete, drawing together findings from multiple experimental studies. While RAC usually shows higher permeability indicators, like greater water absorption and deeper carbonation, these traits are actually tied to the attached mortar and extra interfacial transition zones. They do not come from the recycled aggregates themselves. Crucially, its resistance to sulfate attack and long-term durability can match regular concrete. To achieve this, you just need to use the right cement chemistry, aggregate processing, and mix design methods. The table reinforces the conclusion that durability performance in recycled aggregate concrete is not intrinsically inferior, but instead highly dependent on controllable design and production parameters.

3.4.3 Frost Durability

An examination of the frost durability of RAC has shown promising results, particularly when engineered to optimize air void structures and minimize permeability (Maleševet al., 2010). The innovative use of specific admixtures, alongside selecting high-quality recycled aggregates, is essential for ensuring satisfactory performance under long-term exposure to freezing conditions (Richardson et al., 2016).

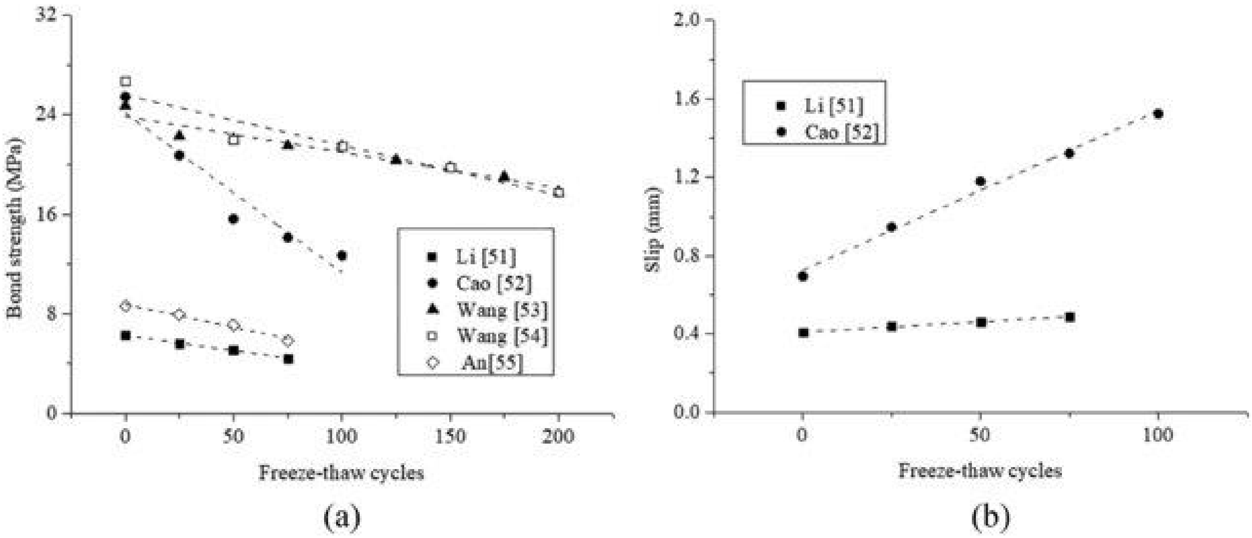


Figure 26 (a) Bond strength degradation with increasing freeze–thaw cycles; (b) Corresponding increase in slip response under cyclic freezing conditions.(Wang et al., 2024)

Figure 27 illustrates the influence of repeated freeze–thaw cycles on the bond performance of recycled aggregate concrete, focusing on both bond strength degradation and slip behavior. As Figure 27(a) shows, bond strength drops steadily as freeze–thaw cycles increase. This happens because the freezing and thawing of pore water creates internal stress, causing microstructural damage. In RAC, this breakdown is closely tied to higher porosity and the presence of multiple interfacial transition zones. Additionally, Figure 27(b) demonstrates that slip values go up with more freeze–thaw exposure, which proves that the mechanical interlock and the bond between the aggregate and paste have weakened. Despite these trends, the rate of deterioration varies among studies, suggesting that optimized air-void systems, controlled permeability, and high-quality recycled aggregates can significantly mitigate frost-related damage. These findings support the conclusion that frost durability in recycled aggregate concrete is highly dependent on material selection and mix design rather than being an inherent limitation of recycled aggregates.

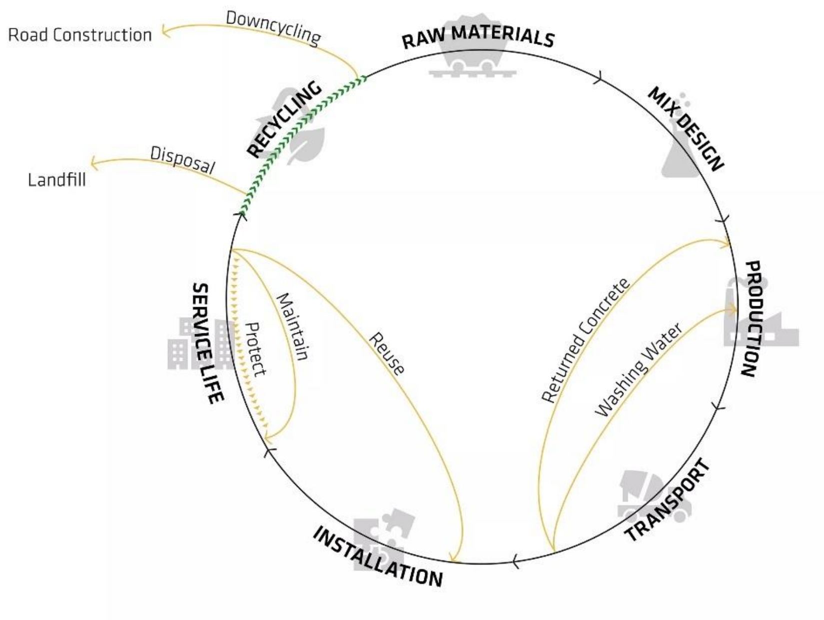


Figure 27 Circular lifecycle of concrete highlighting durability, reuse, recycling, and downcycling pathways. (*Enable Circularity - Make Concrete More Resource Efficient*)

Figure 28 shows a circular lifecycle framework for concrete, highlighting how durability extends its service life and opens up better end-of-life options. The diagram tracks how early decisions during raw material choice, mix design, manufacturing, and installation affect long-term performance. Making concrete durable cuts down on maintenance and delays demolition, which locks in the material's value and embodied energy. When its service life finally ends, the concrete can go down a few different paths: reuse, recycling into fresh concrete, downcycling for road construction, or going to a landfill. Ultimately, better durability—especially against freeze–thaw damage—keeps the aggregates intact and stops the microstructure from breaking down, making reuse and high-quality recycling much easier. This framework proves that frost durability is more than just a performance metric; it is a key factor in how well recycled aggregate concrete fits into a circular economy.

3.5 Environmental Performance & Life Cycle Assessment (LCA)

3.5.1 Environmental Advantages of RAC

The environmental benefits associated with the use of RAC are multifaceted. By diverting waste from landfills and reducing the demand for virgin aggregates, RAC contributes to significant reductions in carbon emissions associated with concrete production (Pedro et al., 2019). Moreover, the recycling process conserves natural resources and minimizes ecological disruption caused by aggregate extraction (Wang et al., 2019).

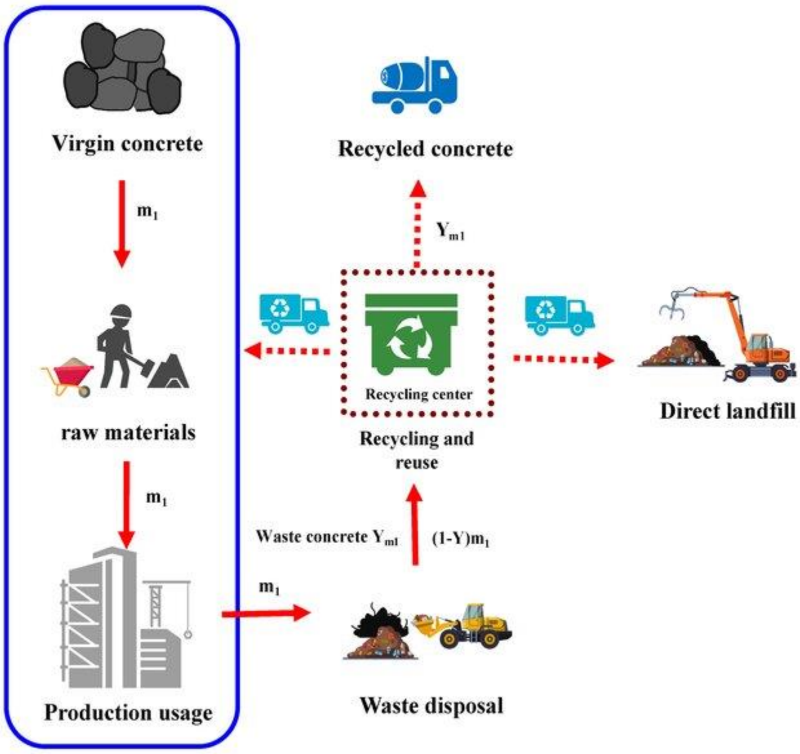


Figure 28 Material flow comparison between conventional concrete production and recycled aggregate concrete pathways(Lei et al., 2022)

Figure 29 compares the material flows of conventional concrete production against recycled aggregate concrete (RAC) pathways. In the conventional system, raw virgin materials are dug up, processed, and used directly in construction. Once that concrete reaches its end of life, it is mostly sent to a landfill, creating a linear flow that hurts the environment. On the other hand, the RAC pathway uses a recycling center to catch waste concrete at the end of a building's service life. Part of this waste is processed and p ut back into the production cycle as recycled aggregates. This cuts down on the need for virgin materials and reduces the amount of waste going to landfills.

This figure shows the environmental benefits of RAC by mapping out a closed-loop system. Instead of dumping everything, only a small amount of waste goes to the landfill, while the rest is used to make new concrete. This system reduces extraction-related emissions, conserves natural resources, and mitigates the environmental impacts associated with construction and demolition waste. By emphasizing recycling and reuse, the diagram reinforces the role of RAC as a key mechanism for transitioning from a linear construction model toward a circular economy, aligning material efficiency with sustainability objectives in concrete production.

Table 11 Comparison of key environmental aspects between conventional concrete and recycled aggregate concrete

Environmental Aspect	Conventional Concrete	Recycled Aggregate Concrete	Key Benefit
Aggregate sourcing	Virgin quarrying	CDW recycling	Reduced land use
Landfill disposal	High	Low	Waste diversion
CO_2 emissions	Higher	Lower	Emission reduction
Resource depletion	High	Reduced	Material conservation
Ecological impact	Significant	Lower	Biodiversity protection
Sensitivity to curing conditions	Moderate	High	Extended curing significantly benefits RAC performance
Curing conditions	Duration and quality of curing	Longer curing improves strength development in RAC	Extended curing is especially important for high RAC content mixes

Table 11 provides a comparative overview of the principal environmental differences between conventional concrete and recycled aggregate concrete.

Conventional concrete relies on virgin aggregates obtained through quarrying, which contributes to land disturbance and habitat loss. By using construction and demolition waste as recycled aggregates, RAC reduces the demand for virgin materials.

The table also shows that RAC decreases landfill disposal by returning recycled aggregates to the concrete production cycle.

This diversion of waste not only alleviates landfill pressure but also contributes to lower overall carbon dioxide emissions by reducing extraction, processing, and transportation demands. Additionally, RAC supports material conservation by slowing the depletion of finite natural resources and mitigating broader ecological impacts. Collectively, these advantages reinforce the role of recycled aggregate concrete as a key material strategy for improving the environmental performance of concrete within a circular economy framework.

3.5.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is an essential methodological framework employed to evaluate the environmental impacts of concrete—from production and use to disposal stages. Various studies utilizing LCA methodologies have indicated that RAC may exhibit lower life cycle emissions compared to conventional concrete, thereby supporting its broader adoption (Bravo, Silva, et al., 2015). This approach enables stakeholders to better understand how RAC performs within the context of sustainable construction practices.

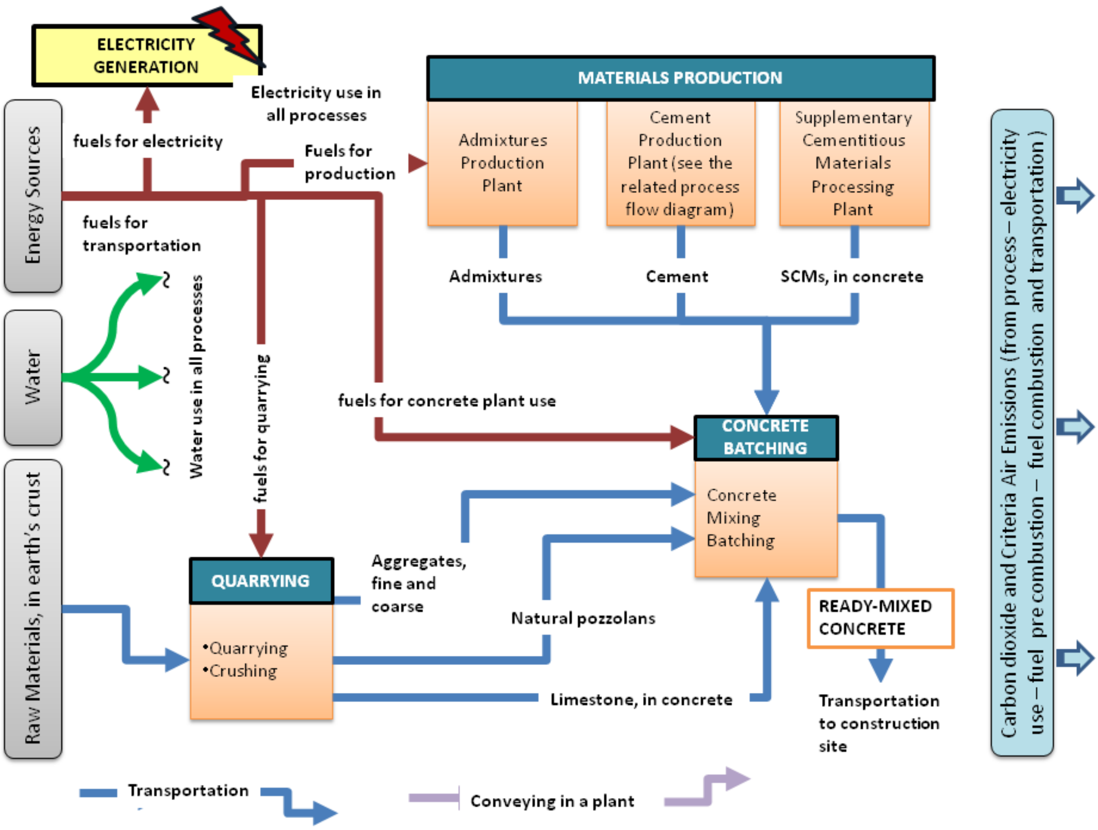


Figure 29 System boundary and process flow diagram for life cycle assessment of conventional concrete production. (*Green Concrete LCA Web Tool*)

Figure 30 illustrates the system boundaries and material–energy flows typically considered in a life cycle assessment (LCA) of conventional concrete production. The diagram highlights the interconnected stages involved in concrete manufacturing, including raw material extraction, quarrying and crushing of aggregates, cement and supplementary cementitious material production, concrete batching, and transportation to the construction site. Each stage carries both direct and indirect environmental burdens, especially when it comes to energy consumption, water use, and carbon dioxide emissions.

A key point highlighted by this system boundary is that cement production causes most of the environmental impact. This is driven by both fuel combustion and electricity use during clinker production and grinding. Additionally, aggregate quarrying and transportation add to these emissions through fuel consumption and power demands.

The figure also demonstrates how auxiliary processes—such as admixture production and ready-mixed concrete batching—contribute cumulatively to the life cycle footprint, even if their individual impacts are comparatively smaller.

By mapping out energy sources, water inputs, and emission pathways, the figure shows how an LCA captures the full environmental profile of concrete instead of looking at isolated processes. This big-picture view is essential when comparing conventional concrete with recycled aggregate concrete. It helps identify ways to cut impacts through material substitution, less quarrying, and shorter transport distances. Ultimately, this system-based approach forms the framework used in LCA studies to prove the environmental benefits of RAC over regular concrete.

Table 12 Comparison of key life cycle assessment indicators for conventional concrete and recycled aggregate concrete

LCA Indicator	Conventional Concrete	RAC	Comparative Outcome
Global warming potential	High	Lower	RAC favorable
Energy demand	High	Moderate	RAC favorable
Water use	Moderate	Slightly higher	Context dependent
Resource depletion	High	Reduced	RAC favorable
End-of-life impact	Disposal-focused	Recycling-focused	RAC favorable

Table 12 compares the main life cycle assessment (LCA) indicators of conventional concrete and recycled aggregate concrete (RAC) based on findings reported in the literature. Overall, RAC shows lower environmental impacts in several categories. In particular, global warming potential and cumulative energy demand are generally lower because less virgin aggregate is required and less construction and demolition waste is sent to landfill.

RAC also helps conserve natural resources by replacing part of the virgin aggregates with recycled materials. At the end of its service life, conventional concrete is usually disposed of, whereas RAC allows materials to be recovered and reused, making it more consistent with circular economy principles. Water consumption may be slightly higher because recycled aggregates often require washing and additional processing. However, this depends on the recycling process and can be reduced by improving water management and using closed-loop recycling systems.

Overall, the table reinforces the conclusion that, from a life cycle perspective, RAC performs favorably across most environmental indicators when compared to conventional concrete. These findings support the integration of RAC within sustainable construction strategies, provided that local production conditions and material quality controls are appropriately managed.

3.5.3 Challenges and Limitations

Despite promising outcomes from LCA studies, challenges persist. Differences in how recycled aggregates are made and quality-controlled can introduce uncertainty into LCA results. At the same time, current regulations might not fully support or encourage the use of RAC, which holds back its mainstream acceptance (Bravo, Silva, et al., 2015; Silva et al., 2016). Ongoing teamwork among researchers, industry professionals, and lawmakers is necessary to solve these problems and help RAC play a bigger role in sustainable construction.

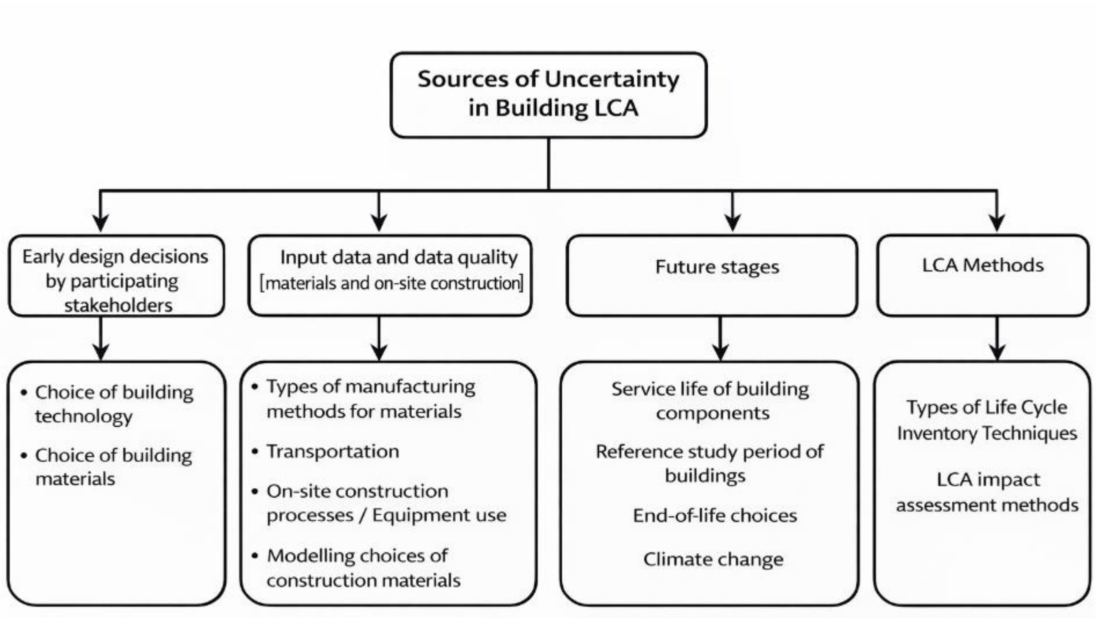


Figure 30 Main sources of uncertainty in building life cycle assessment (LCA). (Warrier et al., 2024)

Figure 31 illustrates the principal sources of uncertainty associated with life cycle assessment in the context of buildings and construction materials. These uncertainties arise across multiple stages of the LCA process, beginning with early design decisions and extending through material selection, construction processes, service life assumptions, and end-of-life scenarios. In the case of recycled aggregate concrete, such uncertainties are particularly pronounced due to the inherent variability of recycled materials and the diversity of recycling pathways.

Early-stage design choices, including the selection of materials and construction technologies, can significantly influence LCA outcomes, often before detailed data are available. Input data quality represents another major source of uncertainty, as environmental inventories for construction materials may vary depending on manufacturing methods, geographic location, and data sources. This issue is especially relevant for RAC, where aggregate properties, processing techniques, and transportation distances can differ substantially between projects.

Additional uncertainty is introduced by assumptions related to service life, future maintenance strategies, and end-of-life scenarios. The long-term performance of recycled concrete components, potential reuse pathways, and evolving climate conditions all affect impact calculations but are difficult to predict accurately. Furthermore, methodological choices within LCA itself—such as system boundaries, impact assessment methods, and allocation rules—can lead to divergent results even when analyzing similar material systems.

Overall, the figure highlights that LCA results should not be interpreted as absolute values but rather as informed estimates subject to contextual limitations. Recognizing and transparently addressing these sources of uncertainty is essential for the responsible use of LCA as a decision-support tool, particularly when comparing conventional concrete with recycled aggregate concrete. This reinforces the need for cautious interpretation, sensitivity analysis, and standardized assessment frameworks when applying LCA in sustainable construction research and practice.

Table 13 Key technical, methodological, regulatory, economic, and cultural challenges affecting the environmental assessment and adoption of recycled aggregate concrete

Challenge Type	Description	Impact	Comparative Outcome
Technical	Variable aggregate quality	Performance uncertainty	RAC favorable
Methodological	Inconsistent LCA boundaries	Non-comparable results	RAC favorable
Regulatory	Restrictive standards	Limited adoption	Context dependent
Economic	Processing costs	Reduced competitiveness	RAC favorable
Cultural	Industry conservatism	Resistance to change	RAC favorable

Table 13 synthesizes the primary challenges influencing both the environmental evaluation and practical implementation of recycled aggregate concrete. For recycled aggregate concrete, these uncertainties are even stronger because recycled materials vary so much and follow many different recycling paths.

Early choices made during the design phase—like picking materials and construction methods—heavily influence LCA results, usually before you even have detailed data. The quality of the input data is another big source of uncertainty. Environmental data for building materials changes based on manufacturing methods, geographic location, and where the data came from. This is a major issue for RAC, where aggregate properties, processing methods, and transport distances can change completely from one project to the next.

More uncertainty comes from assumptions about service life, future maintenance plans, and what happens to the material at the end of its life. It is hard to accurately predict how recycled concrete parts will perform over the long term, whether they can be reused, and how changing climate conditions will affect them. On top of that, choices made within the LCA method itself, like setting system boundaries, impact assessment methods, and allocation rules—can give entirely different results for the exact same materials.

Overall, the figure shows that LCA results are not absolute values. Instead, they should be viewed as informed estimates that depend heavily on the context of the project.

Together, these interconnected challenges highlight that advancing the use of recycled aggregate concrete requires coordinated efforts across technical innovation, policy reform, economic incentives, and professional education, rather than isolated material improvements alone.

3.6 Standards and Regulations

3.6.1 Current Standards

The applicability of recycled aggregate concrete (RAC) in structural practice is strongly governed by existing standards and national regulations, which define acceptable replacement rates of natural aggregates as a function of aggregate quality, exposure conditions, and structural use. As highlighted by (Bakhoum & Mater, 2022), European regulations have progressively moved toward a controlled acceptance of recycled aggregates, while maintaining conservative limits to ensure structural reliability and durability.

At the European level, EN 206 permits the use of recycled concrete aggregates (RCA) provided they meet defined quality classes. In particular, Type A recycled aggregates, consisting of at least 90% crushed concrete and natural stone, may be used in structural concrete.

For reinforced concrete exposed to normal environments, EN 206 usually limits the replacement of coarse natural aggregates to 30% by mass. You can use higher replacement ratios for non-structural jobs—like plain concrete, foundations, and pavements—as long as you meet durability and quality control standards. Using fine recycled aggregates is much more restricted because they absorb too much water and vary a lot in quality (Bakhoum & Mater, 2022).

In Italy, these rules are even stricter under the Norme Tecniche per le Costruzioni (NTC 2018), which takes a very cautious approach to RAC. The Italian code mostly allows recycled aggregates in non-structural elements and low-stress structural parts, such as foundations, substructures, and plain concrete. For reinforced structural concrete, NTC 2018 generally caps the replacement of natural coarse aggregates at moderate levels, usually no more than 30%. Even then, the recycled aggregates must come from controlled sources and meet EN 206 requirements. Additional verification of mechanical and durability performance is required on a case-by-case basis.

Overall, as emphasized by (Bakhoum & Mater, 2022) current standards do not prohibit the use of recycled aggregate concrete, but rather regulate it through explicit quantitative limits and quality requirements. These regulatory constraints reflect a cautious but evolving acceptance of RAC, where partial replacement strategies are favored as a balance between structural safety, durability assurance, and sustainability objectives. This regulatory framework supports the thesis argument that RAC is a conditionally accepted structural material, whose broader implementation depends on performance-based design approaches and future updates to standards rather than on fundamental technical inadequacy.

Table 14 Allowed use of recycled aggregates in concrete according to EN 206 and Italian NTC 2018

Regulation / Standard	Type of recycled aggregate	Structural application	Maximum replacement rate (coarse aggregate)
EN 206 (Europe)	Type A RCA (≥90% crushed concrete/natural stone)	Reinforced structural concrete	≤ 30%
EN 206 (Europe)	Type A RCA	Non-structural concrete (plain concrete, foundations, pavements)	> 30% (case-dependent)
EN 206 (Europe)	Fine recycled aggregates	Structural concrete	Generally restricted
NTC 2018 (Italy)	RCA from controlled sources	Reinforced structural concrete	≤ 30%
NTC 2018 (Italy)	RCA	Non-structural / lightly stressed elements	Allowed
NTC 2018 (Italy)	Mixed CDW aggregates	Structural concrete	Not permitted

3.6.2 European Context

Within the European Union, major efforts are underway to update regulations so the industry can better use recycled materials. New recommendations from EU directives push for higher allowed percentages of recycled aggregates. This helps boost market demand and supports a circular economy in the construction sector (Jaramillo et al., 2023). Standardizing RAC in this way helps make the material more widely accepted and used across different types of building projects.

3.7 Adoption Barriers (Technical & Regulatory)

Figure 32 illustrates technical, regulatory, economic, and socio-cultural barriers that collectively limit the widespread use of recycled aggregates, highlighting the systemic nature of adoption challenges.

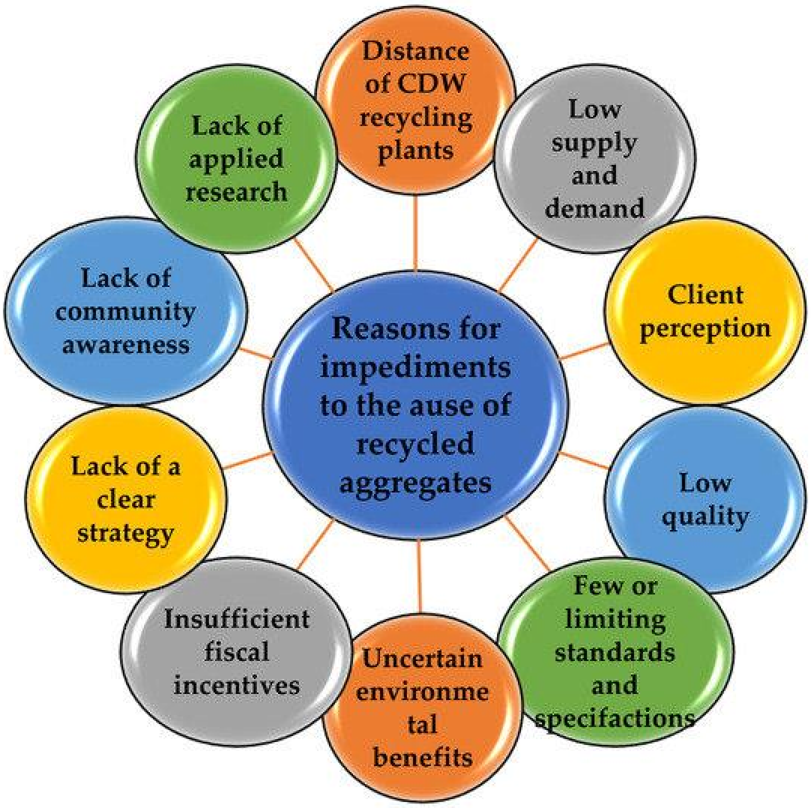


Figure 31 Key factors impeding the adoption of recycled aggregate concrete in construction practice.

Figure 32

brings together the main barriers that hold back the widespread use of recycled aggregate concrete (RAC) in modern construction. Instead of coming from just one issue, the resistance to recycled aggregates comes from a complex mix of technical, regulatory, economic, and socio-cultural factors.

Technical concerns—like the perception of low material quality, inconsistent properties, and doubts about long-term performance—are still the most common obstacles. These worries are often made worse by strict or outdated standards that do not take into account recent improvements in material processing and mix design.

Economic and logistical hurdles also make adoption harder. The distance between job sites and construction and demolition waste (CDW) recycling plants can drive up transport costs and emissions. This makes recycled aggregates less competitive compared to local virgin materials. On top of that, a lack of financial incentives and weak market demand hold back investment in recycling facilities, creating a loop that keeps supply low and availability limited Socio-cultural and institutional barriers matter just as much as possible. Client perceptions, a lack of community awareness, and cautious professional habits cause skepticism toward recycled materials, as people frequently link them to lower performance or higher risk. The absence of a clear strategic framework and limited dissemination of applied research further deepen this divide between technical knowledge and practical implementation. Collectively, these interconnected barriers highlight that increasing the use of RAC requires not only material optimization, but also coordinated efforts across policy development, market incentives, professional education, and public awareness.

3.7.1 Technical Barriers

The adoption of RAC faces various technical barriers rooted in perceived performance deficiencies compared to conventional concrete. Concerns regarding reliability, variability in aggregate qualities, and long-term performance often lead to hesitancy among architects and engineers in specifying RAC for structural applications (Bravo-German et al., 2021; Makul et al., 2021).

3.7.2 Regulatory Barriers

On a regulatory level, frameworks governing construction materials frequently lag behind advancements in industry practices. Stricter certification processes, combined with existing norms that usually favor conventional materials, present additional hurdles for the acceptance of RAC. The reluctance of regulatory bodies to endorse regulations accommodating the uncertainties surrounding the long-term performance of RAC complicates its adoption further (Bakhoum & Mater, 2022; Silva et al., 2016).

3.7.3 Cultural Considerations

Culturally, there is apprehension within the industry surrounding the use of recycled materials, often perceived as a second-tier option. A prevailing attitude among construction professionals, driven by concerns over client satisfaction or project reliability, inhibits experimentation with sustainable options like RAC (Bravo, Brito, et al., 2015). Addressing these perceptions through education and advocacy is crucial to promoting the benefits and successes of utilizing recycled materials within projects.

3.8 Conclusion

This literature review elucidates the complexities surrounding both conventional concrete and recycled aggregate concrete, highlighting key areas of research, gaps in existing knowledge, and broader implications for sustainable practices in the construction industry. Understanding these elements is fundamental for advancing the discourse on RAC and ensuring its role as a viable and sustainable construction material.

4 Methodology and Analytical Framework

This chapter defines the methodological approach used to evaluate the feasibility of Recycled Aggregate Concrete (RAC) as a sustainable material option in architectural practice, compared with Natural/Conventional Concrete (NC

Building on the ideas from Chapters 1 to 3—which treat material choice as a design decision and focus on life-cycle thinking and the circular economy, this study uses a comparative, literature-based approach. This method is backed by secondary quantitative data and a clear, simplified framework for calculating life-cycle assessments (LCA).

The main goal is to deliver conclusions that are clear, reproducible, and highly useful for architects when making decisions, all without needing to introduce new laboratory tests or primary data.

The methodology is therefore designed to:

- Summarize peer-reviewed evidence on mechanical and durability performance;
- structure the comparison using consistent indicators and replacement levels;
- quantify embodied-carbon sensitivity using an explicitly stated functional unit and system boundary.

4.1 Research Approach and Methodological Stance

This thesis is analytical and comparative rather than experimental. No laboratory testing or on-site sampling was conducted. Instead, the research summarizes credible evidence from:

- peer-reviewed reviews and experimental studies on RAC properties;
- standards and technical frameworks governing aggregate acceptance;
- European/Italian context reports and LCA boundary conventions when relevant for architectural decision-making.

This approach fits an architecture thesis well because it focuses on specification-level feasibility—like trade-offs, thresholds, constraints, and risks—rather than laboratory-scale material testing. At the same time, it avoids “narrative review” weakness by using explicit selection criteria and a structured extraction template (Sections 4.3–4.4).

4.2 Research Design and Comparative Logic

The research design treats NC and RAC as two concrete categories evaluated under aligned assumptions and boundary conditions, with the guiding question:

Under what conditions (replacement ratio, aggregate quality class, exposure sensitivity, logistics) can RAC be specified as an architecturally and environmentally preferable material without unacceptable performance penalties?

To operate this, the comparative logic is implemented through four sequential stages:

1. Evidence acquisition and screening:

   Identify studies and reports that clearly report recycled aggregate type (concrete-origin vs mixed), replacement ratio, and test/LCA conditions.

2. Normalization and standardization:

   Harmonize results by focusing on:

   - a common set of indicators.
   - comparable ages/exposure conditions.
   - relative change vs NC when absolute values differ by study.

3. Cross-study synthesis (ranges + conditions):

   Where results vary, the thesis reports ranges and links them to explanatory variables (e.g., adhered mortar content, water absorption, ITZ effects), rather than selecting one “representative” value.

4. Architectural interpretation:

   Translate engineering results into design-facing guidance: feasible substitution ranges, exposure-class caution zones, procurement/supply-chain conditions, and decision rules for specification.

This structure ensures the thesis does not merely “summarize literature” but produces a coherent analytical framework aligned with your research questions.

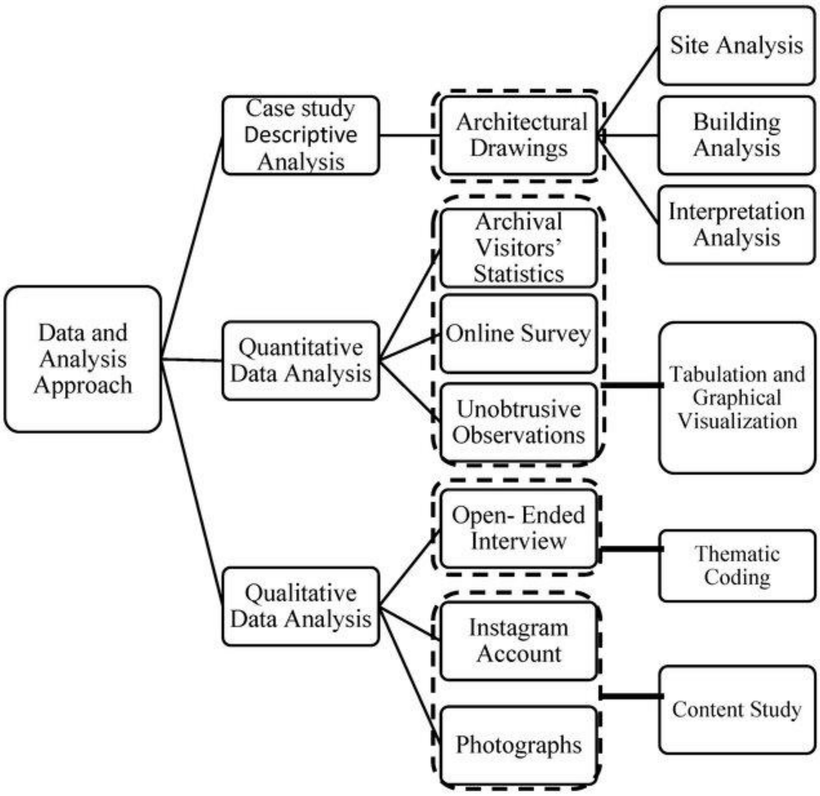


Figure 32 Conceptual organization of data sources and analytical methods within a mixed-methods research framework, illustrating the integration of descriptive case-study analysis, quantitative data analysis, and qualitative inquiry through multiple evidence streams and interpretation techniques. (Saffar & Aoul, 2025)

Figure 33 shows a generalized mixed-methods framework that organizes different data sources and analysis techniques into a clear research structure. The diagram illustrates how architectural research can combine descriptive, quantitative, and qualitative analysis through parallel, connected paths. For example, case study analysis relies on architectural drawings and spatial documentation to look at form, materials, and context. Quantitative analysis uses structured data like archival statistics, online surveys, and observations, which are then turned into tables and charts to find measurable trends. At the same time, qualitative analysis uses open-ended interviews, photos, and digital content, using thematic coding to draw out deeper insights.

In this thesis, the diagram serves as a conceptual model rather than a literal step-by-step data collection guide. It supports the comparative approach used in Section 4 by showing how complex architectural questions can be answered through a structured overview rather than isolated methods. Even though this specific study does not use primary surveys, interviews, or field observations, the diagram supports the thesis's core method: bringing together different types of evidence like mechanical performance data, durability indicators, and environmental metrics into a single, unified framework.

By positioning technical evidence, contextual interpretation, and design-facing synthesis within a single methodological structure, the figure underscores the thesis's commitment to transparency, coherence, and decision-oriented architectural research.

4.3 Data Sources, Search Strategy, and Selection Criteria

4.3.1 Data sources

The study uses three input categories:

- Peer-reviewed syntheses/reviews that report quantitative ranges for recycled aggregate properties and RAC performance (e.g., physical properties, strength reductions, durability sensitivity).
- Institutional/technical references that clarify European practice (e.g., classification logic, policy/market context, boundary conventions that influence comparability).
- Standards and acceptance logic referenced through technical literature (e.g., the need to define replacement ratio, constituent composition, and exposure relevance).

4.3.2 Search strategy and screening logic

A structured search and screening approach is adopted to reduce bias and improve traceability. As a benchmark methodological model, recent systematic review practice (PRISMA-style screening) is used as a reference for how the literature body can be filtered into eligible studies (Junior et al., 2025).

Keyword families (typical): "recycled aggregate concrete", "recycled concrete aggregate", "mechanical properties", "durability", "chloride diffusion", "carbonation", "freeze–thaw", "water absorption", "LCA", "embodied carbon", "A1–A3".

Screening levels:

- Title/abstract relevance to RAC vs NC comparison;
- Full-text eligibility based on reporting clarity (replacement ratio; aggregate type; test conditions or LCA boundary).

The literature selection followed a structured screening process informed by the PRISMA 2020 framework, adapted to the scope and scale of an architectural and engineering-focused comparative review.

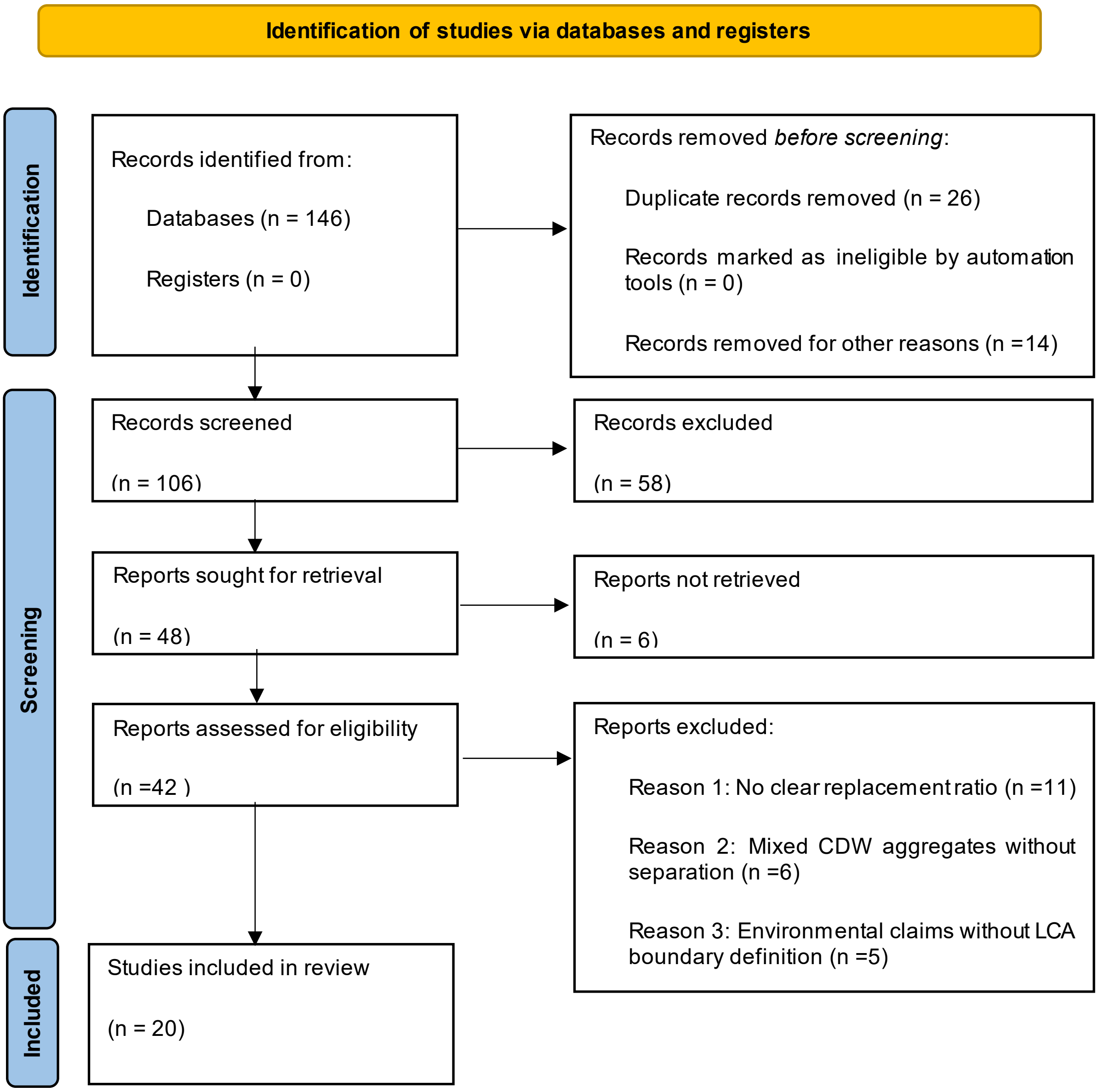


Figure 34. PRISMA-based screening process adopted in this study (Author's elaboration based on the PRISMA 2020 framework; Page et al., 2021).

It should be noted that the PRISMA-based screening applies only to studies used for quantitative and comparative synthesis, while additional references are used throughout the thesis to support conceptual framing, policy context, and interpretative discussion.

4.3.3 Inclusion / exclusion criteria

To ensure methodological consistency, sources are prioritized when they satisfy at least one of the following:

Inclusion criteria:

- Explicit recycled aggregate type and/or quality description (e.g., adhered mortar, absorption, density).
- Clear replacement ratio (0%, 25%, 50%, 100% or comparable levels) (Junior et al., 2025).
- Reported mechanical indicators (compressive strength; tensile/flexural; modulus).
- Durability indicators or mechanisms (absorption/porosity; shrinkage trends; permeability/transport).
- Environmental results described under explicit LCA boundary logic (cradle-to-gate vs extended) or boundary components consistent with European conventions.

Exclusion criteria:

- Studies not specifying replacement ratio or mixing/testing conditions;
- Results not separable between mixed CDW aggregate and concrete-origin aggregate (when the objective is RAC specification);
- Environmental claims without boundary definition (because comparability collapses).

4.4 Comparative Parameters and Performance Indicators

To keep the comparison stable across diverse studies, indicators are grouped into three parameter sets that correspond to your thesis pillars.

4.4.1 Mechanical performance parameters

Mechanical performance is assessed using indicators most frequently reported across the RAC literature:

- Compressive strength (commonly at 28 days, where available);
- Tensile/flexural strength indicators (as available);
- Elastic modulus (highly sensitive to recycled aggregate stiffness and adhered mortar);
- Supporting descriptors (density, workability trends) when they explain feasibility.

To anchor interpretation, the thesis emphasizes relative change vs Natural Concrete (NC), rather than presenting isolated absolute values from single studies. This is consistent with review evidence showing that performance outcomes depend strongly on recycled aggregate quality and replacement ratio. For example, systematic synthesis reports compressive strength reductions spanning approximately 2.6% to 43%, depending on replacement rate and aggregate characteristics (Junior et al., 2025).

4.4.2 Durability performance parameters

Durability is treated as an exposure-sensitive mechanism rather than a single property. Indicators include:

- Water absorption/permeability tendency (as a proxy for transport of aggressive agents).
- Shrinkage and time-dependent effects (serviceability relevance).
- Chloride/carbonation sensitivity when available in sources used later in Chapter 5.
- Freeze–thaw sensitivity when available.

A key methodological decision is to explicitly connect durability outcomes to material microstructure. Review evidence identifies major physical differences between natural coarse aggregate (NCA) and recycled concrete aggregate (RCA), particularly the adhered mortar fraction and associated porosity. Reported ranges show RCA typically have:

- specific gravity around 2.1–2.5 (vs NCA 2.4–2.9),
- bulk density around 1200–1425 kg/m^3 (vs NCA 1450–1750 kg/m^3),
- absorption around 3–12 wt% (vs NCA 0.5–4 wt%),
- pore volume around 5.0–16.5 vol% (vs NCA 0.5–2 vol%) (Safiuddin et al., 2013).

These ranges justify why the thesis treats transport properties (absorption/permeability and ITZ-driven pathways) as central durability drivers rather than optional descriptors.

Table 15 Comparison of physical properties of natural aggregates (NA) and recycled concrete aggregates (RCA) across different particle size fractions, including bulk density, bulk specific gravity (SSD), moisture content, and water absorption. (Biglarijoo et al., 2012)

Physical Properties	Bulk Density (gr/cm^3)		Bulk Specific Gravity(SSD) (gr/cm^3)		Moisture Content (%)		Absorption (%)	
	N.A.	RCA	N.A.	RCA	N.A.	RCA	N.A.	RCA
(12.5-19) mm	1.46	1.27	2.70	2.48	0.22	1.37	0.6	4.72
(9.5-12.5) mm	1.46	1.25	2.70	2.46	0.20	1.48	0.52	5.56
(6.35-9.5) mm	1.47	1.23	2.70	2.46	0.24	1.71	0.48	6.00
(4.75-6.35) mm	1.50	1.20	2.69	2.42	0.28	2.14	0.78	7.62
(2.36-4.75) mm	1.55	1.20	2.70	2.39	0.45	2.00	0.75	7.14
(1.18-2.36) mm	1.53	1.17	2.70	2.39	0.86	2.67	1.01	8.50
(0.6-1.18) mm	1.50	1.14	2.55	2.34	1.37	4.83	4.61	12.64
(0.3-0.6) mm	1.47	1.11	2.55	2.33	1.78	5.79	5.60	17.34
(0.15-0.3) mm	1.44	1.10	2.51	2.07	2.77	7.76	7.04	22.20

Table 15 gives a detailed comparison of the main physical properties of natural aggregates (NA) and recycled concrete aggregates (RCA) across different particle sizes. This data offers important insights into how recycled aggregate concrete behaves over time. Across all size ranges, RCA consistently has a lower bulk density and bulk specific gravity than NA. This happens because of the old cement mortar stuck to the recycled aggregates and their higher internal porosity. This drop in density is even more noticeable in the finer sizes, showing that the crushing process tends to leave the weaker, more porous mortar in the smaller particle fractions.

Moisture content and water absorption show the biggest differences between NA and RCA. While natural aggregates have low, stable absorption values—usually below 1%RCA absorption jumps sharply as the particle size gets smaller, passing 20% in the finest fractions.

This trend highlights the strong correlation between particle size reduction, adhered mortar content, and pore connectivity within recycled aggregates. From a durability perspective, elevated absorption directly translates into increased susceptibility to water ingress, enhanced transport of aggressive agents, and greater sensitivity to environmental exposure conditions such as freeze–thaw cycles, carbonation, and chloride penetration.

These physical property differences justify the methodological emphasis placed in this thesis on transport-related durability mechanisms rather than on isolated strength values.

The data in Table 15 explains why current standards favor using coarse recycled aggregates in structural concrete, while often restricting fine recycled aggregates or capping their replacement levels. On top of that, the big differences between these size ranges show why you need tight control over aggregate grading. When designing recycled aggregate concrete for projects where durability is a priority, you must use pre-saturation methods and careful mix adjustments to handle these variations.

These material-property contrasts (Table 15) justify treating durability performance as transport- and ITZ-controlled rather than as a single-value material property.

4.4.3 Environmental performance parameters

The primary environmental metric is:

- Embodied CO_2 per cubic meter of concrete (kg CO_2 eq/m^3)

This matches the embodied-carbon framing in earlier chapters and is interpretable in architectural quantities (volumes of slabs, beams, cores).

4.5 Boundary Conditions and LCA Approach

Environmental comparisons are highly sensitive to system boundaries. Therefore, this thesis applies an explicitly stated boundary logic consistent with European LCA/EPD conventions, where product stage impacts are typically reported as Modules A1–A3 (raw material supply, transport, manufacturing).

4.5.1 Boundary selection (cradle-to-gate, A1–A3)

The analysis adopts a cradle-to-gate boundary focusing on Modules A1–A3. This choice is made because:

- It aligns with the most commonly reported boundary in comparative RAC literature.
- It reduces speculative uncertainty from project-specific use-phase and end-of-life modeling while still capturing the dominant production-stage burdens (especially cement).

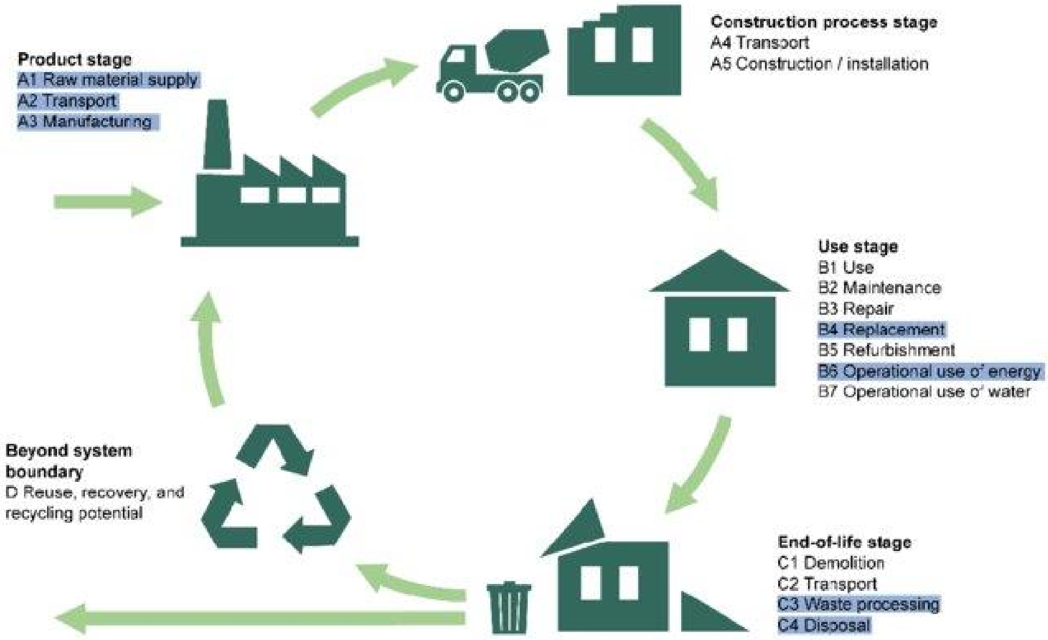


Figure 35 Life-cycle stages of buildings and construction materials according to the modular LCA framework, illustrating product stage (A1–A3), construction stage (A4–A5), use stage (B1–B7), end-of-life stage (C1–C4), and beyond-system-boundary benefits (Module D). (Zimmermann et al., 2021)

Figure 35 schematically represents the life-cycle assessment (LCA) structure commonly adopted for buildings and construction materials under European standards, organizing environmental impacts into modular stages from raw material extraction to end-of-life and potential recycling benefits. The product stage (Modules A1–A3) encompasses raw material supply, transport, and manufacturing processes, and is widely recognized as the dominant contributor to embodied carbon in concrete due to the energy intensity of cement production and aggregate processing.

The later stages include construction and installation (A4–A5), the use phase (B1–B7), end-of-life processes (C1–C4), and an optional Module D, which tracks reuse, recovery, and recycling benefits outside the main system boundary.

For this thesis, the cradle-to-gate boundary (A1–A3) was intentionally chosen to keep the method transparent, comparable, and reliable. As Figure 35 shows, extending the boundary to include use-phase or end-of-life modules adds a lot of project-specific uncertainty. These uncertainties come from guessing at service life, maintenance schedules, demolition methods, and recycling efficiency. During the early design stages of an architectural project, these details are usually unknown. Forcing them into the equation can confuse comparative results rather than make them clearer. By focusing strictly on Modules A1–A3, the analysis isolates the actual environmental impact of the material choice itself—specifically swapping natural aggregates for recycled ones—without mixing it up with future variables that the architect cannot control.

Figure 35 also explains why transportation (A4) is handled separately through a scenario-based sensitivity analysis instead of a full boundary expansion. While shipping can noticeably shift environmental performance, especially with recycled aggregates—its actual impact depends entirely on local infrastructure and where materials are sourced. Separating product-stage emissions from logistics matches the best practices used in comparative LCA studies and makes the findings highly relevant for real architectural choices.

. In this way, the figure supports the methodological decision to prioritize a cradle-to-gate assessment while acknowledging the broader life-cycle context within which recycled aggregate concrete operates.

4.5.2 Logistics scenarios (sensitivity framing)

Because transport can materially change net benefits, environmental interpretation is structured under two logistics scenarios:

- Local scenario: transport distance ≤ 30 km
- Extended scenario: transport distance ≥ 80 km

This approach links embodied-carbon performance to the feasibility of local circular supply chains and supports your architectural framing (material choice is also an infrastructure choice).

4.6 Calculation Approach, Functional Unit, and Assumptions

4.6.1 Functional unit and reference concrete

The functional unit is defined as:

- 1 m^3 of structural concrete, reference class C30/37 (representative of common structural applications).

4.6.2 Fixed assumptions for transparent comparison

To maintain reproducibility, the thesis applies the following fixed assumptions (kept consistent across NC and RAC scenarios):

- Strength class: C30/37
- Cement content: 340 kg/m^3
- w/c ratio: 0.50
- Replacement levels (coarse aggregate substitution): 0%, 25%, 50%, 100%
- Transport scenarios: 30 km and 80 km
- Emission factors and equation structure as defined in the thesis's calculation framework.

(Important methodological note: cement dominates embodied CO_2; therefore, the model is intentionally structured to keep cement constant so that the isolated effect of aggregate substitution + logistics can be interpreted cleanly.)

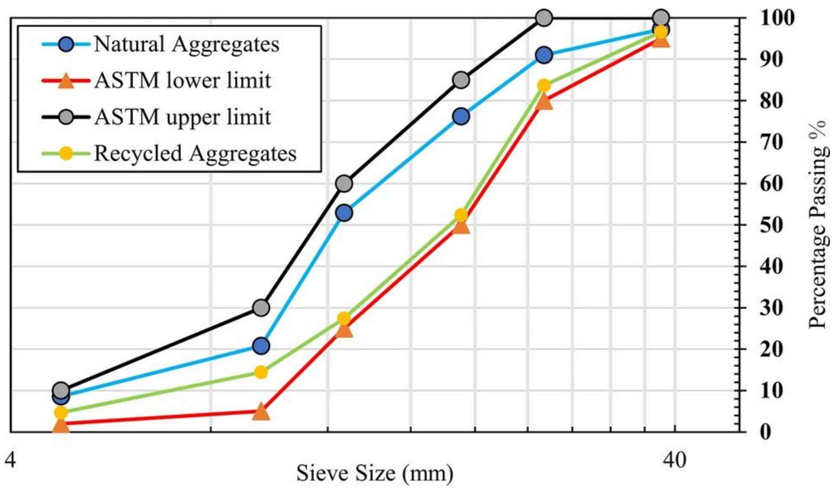


Figure 36 Particle size distribution curves of natural aggregates and recycled aggregates compared with ASTM grading envelope limits, illustrating compliance ranges and deviations relevant to concrete mix design. (Khan et al., 2025)

Figure 36

compares the particle size distribution (PSD) of recycled aggregates with that of natural aggregates, benchmarked against the ASTM lower and upper grading limits. The figure demonstrates that, while recycled aggregates can generally be processed to fall within standard grading envelopes, their distribution curve often deviates from that of natural aggregates, particularly in the intermediate and fine size fractions. These deviations are primarily attributed to the crushing mechanisms applied to construction and demolition waste, which tend to generate a higher proportion of fines and angular particles due to the fragmentation of adhered mortar and weaker cementitious phases.

From a methodological perspective, the grading behavior illustrated in Figure 36 is highly relevant because aggregate grading directly influences fresh and hardened concrete properties, including workability, packing density, and water demand. Recycled aggregates frequently exhibit a steeper PSD curve and increased fines content compared to natural aggregates, which can lead to higher water absorption and reduced workability if mix designs are not adjusted accordingly.

This phenomenon explains why recycled aggregate concrete often requires modified grading optimization, additional water management strategies, or the incorporation of supplementary cementitious materials to maintain comparable rheological behavior to conventional concrete. Importantly, Figure 36 also supports a key assumption adopted in this thesis methodology: recycled aggregate concrete should not be evaluated as a direct, one-to-one material substitution without considering grading control and processing quality. Even when recycled aggregates fall within ASTM grading limits, their internal microstructure— characterized by adhered mortar and higher porosity—can amplify the effects of grading irregularities on durability-related transport properties.

Consequently, the figure reinforces the methodological decision to interpret mechanical and durability performance in relative terms (changes versus NC) and under controlled replacement ratios, rather than assuming equivalence based solely on compliance with grading standards.

Within the analytical framework of Chapter 4, this grading comparison provides a mechanistic bridge between aggregate-level properties and performance outcomes discussed later in Chapter 5.

As replacement levels go up, the elastic modulus typically drops by 10% to more than 30%. While these reductions might not matter much for ultimate strength design, they can directly impact deflection control, vibration behavior, and how cracks develop. For architects, these are critical factors to consider when working on structural detailing.

4.6.3 Simplified embodied-carbon equation

Embodied CO_2 is calculated using:

- Total embodied CO_2 = Σ (quantity of material × emission factor)

Where quantities are in kg per m^3 of concrete and emission factors are in kg CO_2 per kg material.

4.7 Evidence Extraction Template and Coding Logic

To avoid inconsistent interpretation across studies, each eligible source is coded using a structured template capturing:

- Aggregate type (concrete-origin RCA vs mixed CDW aggregate if specified).
- Replacement ratio (%).
- Key recycled aggregate descriptors (absorption, density, adhered mortar if reported).
- Mix descriptors were available (w/c, cement content, SCM usage).
- Mechanical outputs (fc, ft/flex, E).
- Durability proxies (absorption, shrinkage, transport/diffusion, where available).
- Environmental boundary (A1–A3 vs extended) when reported.

This coding structure is consistent with the state-of-the-art understanding that recycled aggregate performance is governed by adhered mortar and absorption/porosity ranges rather than by "recycled" status alone.

Table 16 Data extraction and coding framework used for cross-study comparison

Field	Coding / Units	Purpose for comparability
Concrete type	NA / RAC	Defines comparison classes
RA origin	concrete-origin / mixed (if stated)	Separates quality regimes
Replacement ratio	% coarse replacement	Enables dose-response interpretation
Absorption	wt%	Durability & workability proxy
Density (SSD/bulk)	kg/m^3	Stiffness + mix yield implications
Adhered mortar	% (if stated)	Mechanistic driver of strength loss
fc (28d typical)	MPa	Primary mechanical indicator

ft / flex	MPa	Crack-related indicator
Elastic modulus	GPa	Serviceability proxy
Durability metric	test-specific	Exposure relevance
LCA boundary	A1–A3 etc.	Prevents non-comparable LCA claims
Logistics	km	Captures transport sensitivity

4.8 Illustrative Case Study Element (demonstrator)

To translate the methodology into an architectural quantity, the thesis includes an illustrative 1 m^3 structural element comparison under two scenarios:

- NC (0% RCA)
- RAC (50% coarse RCA replacement)

This demonstrator is not a project-specific simulation; it exists to show how architectural specifications (volume-based take-offs) can connect to embodied-carbon reasoning using the same boundary and assumptions applied throughout the chapter.

4.9 Validity, Limitations, and Quality Control

4.9.1 Quality control measures

A literature-based comparative study is vulnerable to variability in test methods and recycled aggregate feedstock. Therefore, this thesis implements the following controls:

- Triangulation across multiple independent sources to confirm directional consistency;
- Prioritization of sources with clear replacement ratios and reported aggregate properties;
- Reporting ranges and conditions, not single-study universal claims;
- Maintaining explicit LCA boundary and logistics assumptions to avoid hidden variability.

4.9.2 Limitations (explicit scope control)

Key limitations include:

- No experimental calibration.
- Variability of recycled aggregate quality (feedstock and processing dependency);
- Simplified LCA boundary (A1–A3) that does not model C–D modules or project-specific end-of-life credits.
- Regional specificity of assumptions where applicable.

These limitations define scope and improve interpretability; they do not invalidate the comparative framework.

4.10 Chapter Summary

This chapter defined a transparent and reproducible methodology to compare NC and RAC using secondary evidence aligned with architectural decision-making. The framework structures evidence across mechanical performance, durability, and embodied-carbon indicators. It adopts a clear cradle-to-gate system boundary and incorporates scenario-based logistics sensitivity to evaluate the influence of transport distances on sustainability outcomes. The resulting methodology directly supports the interpretation and synthesis developed in Chapter 5.

5 Results and Discussion

5.1 Chapter Overview

This chapter synthesizes and interprets the comparative evidence developed in Chapters 2–4, translating technical findings on recycled aggregate concrete (RAC) into design relevant conclusions for architectural practice. Rather than presenting experimental results, the chapter integrates mechanical performance, durability behavior, and embodied-carbon outcomes into a coherent evaluation framework that supports informed material specification decisions.

The discussion is structured around the three analytical pillars established in the methodology:

- Mechanical performance implications of recycled aggregate substitution.
- Durability behavior and exposure-related constraints.
- Environmental performance and embodied-carbon sensitivity.

By cross reading these dimensions, the chapter identifies feasible substitution ranges, risk thresholds, and conditions under which RAC can be specified without compromising architectural performance or service life.

5.2 Mechanical Performance: Interpretation of Comparative Trends

5.2.1 Strength performance relative to natural aggregate concrete

Across the reviewed literature, the mechanical response of RAC is strongly governed by recycled aggregate quality and replacement ratio. When coarse recycled concrete aggregates (RCA) are used, compressive strength reductions relative to conventional concrete (NC) typically fall within a moderate range at low to intermediate replacement levels, while becoming more pronounced at full substitution.

Synthesized evidence indicates:

- Up to ~25–30% coarse RCA replacement, compressive strength reductions are often negligible or within typical design scatter.
- At ~50% replacement, reductions become more systematic but remain manageable through mix optimization.

- At 100% replacement, compressive strength losses may range from approximately 10% to over 30%, depending on adhered mortar content, water absorption, and original concrete quality.

These trends align with review findings reported by (Junior et al., 2025) and (Safiuddin et al., 2013) which consistently link strength reductions to the lower stiffness and higher porosity of recycled aggregates rather than to "recycled" status per se.

From an architectural standpoint, these results suggest that RAC is mechanically viable for a wide range of structural and non-structural applications, provided that replacement ratios are selected with awareness of strength margins and safety factors.

5.2.2 Elastic modulus and serviceability implications

The elastic modulus of RAC shows a more sensitive response to recycled aggregate incorporation than compressive strength. Even at moderate replacement ratios, reductions in modulus are frequently reported due to:

- Lower intrinsic stiffness of recycled aggregates,
- Increased total mortar content,
- Multi-ITZ microstructure.

Reported reductions in elastic modules commonly range from 10% to over 30% as replacement levels increase. While such reductions may have limited consequences for ultimate strength design, they can influence deflection control, vibration behavior, and crack width development, which are critical parameters in architectural detailing.

Accordingly, the results indicate that:

- RAC is most suitable where serviceability requirements are not stiffness-critical, or
- Were structural depth, reinforcement ratio, or layout can compensate for reduced modulus.

This reinforces the importance of treating RAC as a performance-based material choice, rather than assuming equivalence with NC across all serviceability criteria.

5.3 Durability Behavior: Exposure-Sensitive Interpretation

5.3.1 Transport properties and permeability-related risks

Durability outcomes in RAC are primarily governed by transport-related properties, including water absorption, pore connectivity, and ITZ continuity. Compared to natural aggregates, recycled aggregates typically exhibit:

- Higher absorption (commonly 3–10 times that of natural aggregates),
- Greater pore-volume, (typically 10–30% higher)
- Increased heterogeneity at the aggregate–paste interface.

As discussed in Chapter 4, these characteristics explain why RAC may exhibit:

- Increased permeability, (often 10–50% higher than conventional concrete);
- Higher susceptibility to chloride ingress (reported increases up to 20–40% depending on replacement ratio)
- Accelerated carbonation under unfavorable curing or exposure conditions, (commonly 10–60% greater carbonation depth at high RCA contents).

However, the literature also demonstrates that these risks are not intrinsic failures, but conditional behaviors linked to aggregate quality and mix design. When supplementary cementitious materials, optimized grading, and controlled curing are employed, RAC durability can approach or match that of NC, even at higher replacement ratios.

5.3.2 Exposure classes and architectural applicability

From a design perspective, the results support a differentiated specification strategy:

- For interior or mildly exposed elements, RAC with moderate replacement ratios poses limited durability risk.
- For aggressive exposure environments (chlorides, freeze–thaw, carbonation-sensitive detailing), RAC can still be viable but requires stricter controls on:
    - Aggregate quality,
    - Replacement ratio,
    - Binder composition
    - Curing regime.

This exposure-dependent interpretation aligns with European performance-based durability concepts and reinforces the need to integrate RAC decisions with architectural detailing and environmental context, rather than treating material choice in isolation.

5.4 Environmental Performance and Embodied-Carbon Sensitivity

5.4.1 Aggregate substitution and embodied-carbon reduction

The environmental analysis confirms that the primary embodied-carbon driver in concrete remains cement, while aggregate substitution delivers incremental but meaningful reductions when logistics are favorable.

Under cradle-to-gate (A1–A3) boundaries:

- Replacing natural aggregates with recycled aggregates reduces impacts associated with extraction and processing.
- Landfill diversion further strengthens the circularity rationale.

However, the magnitude of benefit is highly sensitive to transport distance. Local sourcing scenarios consistently outperform extended logistics scenarios, reinforcing the conclusion that RAC is most effective when embedded within regional circular supply chains.

5.4.2 Architectural interpretation of LCA results

Rather than treating RAC as a universal low-carbon solution, the results highlight that:

- RAC provides robust environmental benefits when locally sourced, with reported embodied-carbon reductions commonly ranging between 5% and 20%.
- Benefits diminish when transport distances increase, and may become negligible when long-distance hauling is required
- Cement reduction strategies remain dominant for deep decarbonization, often delivering reductions exceeding 30–50%.

For architects, this implies that RAC should be specified as part of a broader embodied carbon strategy, coordinated with:

- Material sourcing decisions,
- Structural optimization
- Regional infrastructure.

5.5 Integrated Performance Trade-Offs and Design Guidance

By cross-reading mechanical, durability, and environmental results, the thesis identifies three specification regimes:

- Low-risk regime (≈0–30% RCA)

  Minimal mechanical and durability penalties; suitable for most architectural applications.

- Balanced regime (≈30–50% RCA)

  Requires conscious design and exposure awareness; offers meaningful circularity and carbon benefits.

- High-replacement regime (≈50–100% RCA)

  Technically feasible but design-sensitive; appropriate where performance margins, detailing control, and sustainability priorities justify additional complexity.

This framework transforms literature evidence into actionable architectural guidance, directly supporting specification-level decision-making.

Table 17 Integrated interpretation of mechanical, durability, and environmental performance of recycled aggregate concrete as a function of coarse RCA replacement ratio.

Replacement regime	Mechanical performance	Durability sensitivity	Environmental benefit	Architectural interpretation
0–30% RCA	Comparable to NC	Minimal	Limited	Low-risk substitution; broad applicability
30–50% RCA	Moderate reduction; manageable	Exposure aware	Significant (local sourcing)	Balanced regime; design-informed choice
50–100% RCA	Noticeable reductions	High sensitivity	Context dependent	Design-sensitive; selective application

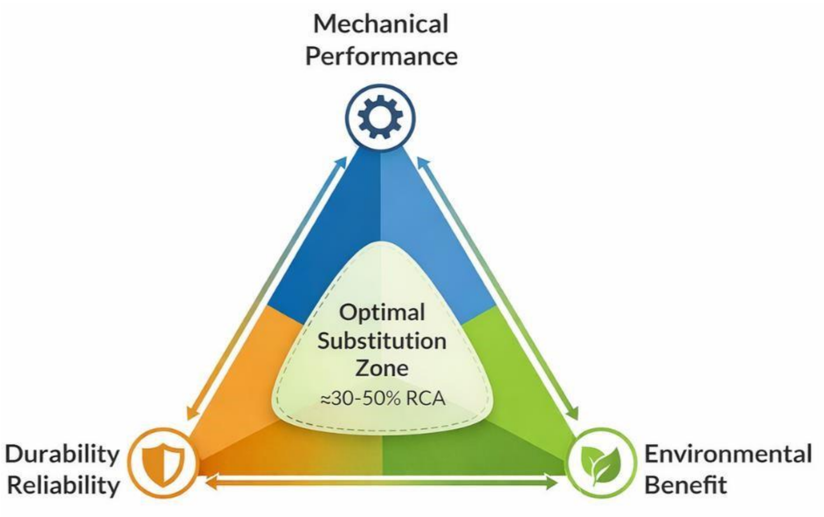


Figure 37 Conceptual synthesis of mechanical, durability, and environmental trade-offs in recycled aggregate concrete, highlighting the optimal substitution range (≈30–50% coarse RCA) for architectural specification.

Figure 37 shows the integrated performance logic that comes out of the comparative analysis in this thesis. Instead of looking at mechanical behavior, durability, and environmental impact as separate issues, the diagram presents recycled aggregate concrete (RAC) as a material system driven by trade-offs between three connected dimensions. Mechanical performance covers the strength and stiffness needed for structural capacity and serviceability. Durability and reliability track exposure sensitivity, transport properties, and long-term service life. Finally, environmental benefit measures embodied carbon reductions and alignment with circular economy goals.

The shaded area in the center highlights the optimal substitution zone—roughly 30–50% coarse recycled aggregate replacement—where these three goals balance out. Within this specific range, any drop in mechanical strength stays manageable and usually falls within normal design margins. At the same time, durability risks can be easily controlled through smart mix choices and detailing, while meaningful environmental benefits are achieved, especially when materials are sourced locally.

At lower replacement levels, mechanical and durability performance closely resemble conventional concrete, but environmental gains are limited. Conversely, at higher substitution ratios, the system becomes increasingly sensitive to reductions in stiffness, increased permeability, and exposure-related durability risks, while environmental advantages may be offset by transport and processing impacts.

This conceptual synthesis reinforces the central argument of the thesis: recycled aggregate concrete should not be judged based on single performance indicators or binary comparisons with conventional concrete.

Instead, its suitability must be judged through a system-based evaluation that matches material behavior with architectural goals, exposure risks, and supply-chain realities. By showing RAC as a balance between competing yet connected criteria, Figure 37 gives architects a clear framework for making evidence-based material choices. This approach supports a shift away from default material selections and toward responsible, performance-driven sustainable design.

5.6 Limitations and Interpretation Boundaries

The discussion remains bound by the methodological limits established in Chapter 4:

- Reliance on secondary data,
- Variability in recycled aggregate quality,
- Simplified LCA boundaries.

Importantly, these limitations do not weaken the conclusions; they clarify the conditions under which conclusions hold, reinforcing transparency and academic rigor.

5.7 Chapter Summary

This chapter synthesized comparative evidence on RAC performance into a design-oriented interpretation framework. The results demonstrate that RAC is not an inferior substitute for conventional concrete, but a conditionally viable material whose performance depends on replacement ratio, aggregate quality, exposure context, and logistics. When these parameters are controlled, RAC can contribute meaningfully to sustainable architectural practice without compromising structural integrity or durability.

6 Conclusions and Recommendations

6.1 Introduction

In this chapter, a summary of the main findings of the study is presented. A discussion on their implications for architectural practice, sustainable construction, and future research is also addressed. This chapter presents the main conclusions of the research that was done based on three main components presented in the previous chapters; building on conceptual framework, literature review, and comparative analysis.

The main goal of this study was to evaluate the potential use of recycled aggregate concrete (RAC) as a practical and sustainable alternative to natural concrete (NC) in architectural applications.

In the literature review, a comparison was made between the two to assess the mechanical performance, durability, and environmental impact of RAC, with special attention to embodied carbon and material selection during the design stage.

6.2 Summary of Key Findings

The principal findings of the research are summarized across three interconnected performance dimensions.

- **Mechanical Performance**

The literature show that RAC can achieve mechanical performance similar to conventional concrete when replacements are done in moderation and used under appropriate production conditions. When using coarse aggregate replacement at levels of 30-50%, the compressive strength of RAC reached 80-95% of that of the compressive strength of conventional concrete. These results were obtained under proper control of aggregate quality, mix design, and curing practices. Although reductions in elastic modulus are consistently reported, these do not preclude structural application and can be accommodated through informed structural design and detailing.

These findings demonstrate that mechanical limitations associated with RAC are conditional rather than inherent, challenging the persistent assumption that recycled aggregates necessarily compromise structural performance.

- **Durability Performance**

Durability emerged as the most sensitive performance category.

The most challenging aspect of recycled aggregate concrete is durability. Increased risk of carbonation, moisture ingress, and chloride penetration because of the higher porosity and adhered mortar in recycled aggregate. However, the literature shows that by using lower water-cement ratios, supplementary cementitious materials, aggregate pretreatment, and proper curing, these effects can be greatly reduced. Under appropriate exposure conditions and moderate replacement levels, RAC can achieve durability comparable to European service life requirements. Therefore, durability should be managed during mix design and material selection rather than a limitation to the use of RAC.

- **Environmental Performance**

One of the main advantages that were identified during the environmental assessment is that when recycled aggregates were locally sourced and partially replaced natural aggregates, embodied CO_2 emissions were reduced by approximately 15-20 % per cubic concrete meter. This means that when construction and demolition waste is reused, CO_2 emissions produced by the extraction of new virgin aggregate are reduced. The analysis also showed that using local recycled aggregates meant a reduction in transportation, which in turn had a major influence on environmental performance. As transport distances increase, the environmental benefits decrease. These findings highlight the importance of local recycling networks for providing recycled aggregates with minimum transportation.

6.3 Addressing the Research Questions

The findings enable explicit responses to the research questions defined in Chapter 1:

- **How does RAC compare to NC in terms of environmental sustainability?**

  RAC offers measurable reductions in embodied carbon, with reported reductions commonly ranging from 5% to 20% under favorable transport conditions and moderate replacement ratios, making it an effective strategy for reducing the environmental footprint of concrete in architectural applications

- **What trade-offs exist in mechanical and durability performance?**

  Trade-offs are present but manageable. Performance reductions are primarily governed by design decisions, exposure conditions, and quality control rather than by the recycled nature of aggregates itself.

- **Under what conditions is RAC most effective?**

  RAC performs most effectively at partial replacement levels (up to approximately 50%), within regional supply networks, and in applications where exposure conditions are clearly understood and addressed through informed design.

- **How can architects integrate RAC into sustainable design strategies?**

Architects can incorporate RAC by treating material selection as an early-stage design decision, aligning structural logic, durability requirements, and environmental objectives within a coherent, performance-based framework.

6.4 Implications for Architectural Practice

Beyond its technical evaluation, this study shows that material selection has important environmental consequences. Concrete has traditionally been treated as the default construction material, but the findings suggest that recycled aggregate concrete offers a practical alternative in many applications.

Recycled Aggregate Concrete enables architects to:

- Reduce embodied carbon without abandoning concrete as a structural material,
- Participate actively in circular economy strategies,
- Reconceptualize construction waste as a design resource rather than an externality.

The main issue preventing the wider use of recycled aggregate concrete is not its technical performance but its limited acceptance in professional practice. With appropriate design, material selection, and quality control, recycled aggregate concrete can provide reliable structural performance while reducing environmental impact.

6.5 Recommendations

Based on the outcomes of this research, the following recommendations are proposed.

- **For Architectural Practice**
    - Integrate embodied-carbon considerations into early design stages rather than late specification phases.
    - Prioritize partial aggregate replacement strategies over full substitution.
    - Collaborate closely with structural engineers and material suppliers to ensure quality control and exposure-appropriate detailing.
    - Apply RAC selectively in structural elements where environmental benefits can be maximized with manageable performance risks.
- **For Policy and Industry**

- Strengthen regional recycling infrastructure to reduce transport-related emissions.
- Simplify and harmonize regulatory pathways for RAC certification in structural applications.
- Promote RAC adoption through public procurement policies and sustainability certification frameworks.

- **For Education and Professional Culture**
    - Strengthen material literacy and life cycle thinking within architectural education.
    - Shift professional narratives from "new equals better" toward circular material value.
    - Support demonstration projects that normalize recycled materials in high quality architectural applications.

6.6 Limitations of the Study

This thesis is subject to several limitations:

- Reliance on secondary data rather than experimental testing,
- Variability in recycled aggregate quality and processing,
- Environmental assessment limited to cradle-to-gate boundaries (Modules A1–A3),
- Primary focus on European and Italian contexts.

These limitations define the scope of the research and enhance interpretability; they do not undermine the validity of the conclusions.

6.7 Future Research Directions

Future research could build upon this work by:

- Conducting long-term field monitoring of RAC structures under real exposure conditions,
- Integrating RAC performance databases into BIM-based LCA tools for early design support,
- Exploring the architectural expression and aesthetic potential of recycled concrete in visible applications,

- Assessing socioeconomic impacts of RAC adoption, including cost structures and employment within recycling industries.

6.8 Final Reflection

This thesis demonstrates that sustainable innovation in architecture does not necessarily require abandoning established materials. Rather, it often begins with rethinking how those materials are sourced, valued, and specified.

Recycled Aggregate Concrete embodies this shift. It transforms waste into opportunity, challenges linear construction models, and enables architects to reduce environmental impact without sacrificing structural integrity or design intent.

Ultimately, architecture bears responsibility not only for shaping buildings, but for shaping material systems that respect environmental limits. By adopting materials such as RAC within informed, performance-based design frameworks, architects can play a decisive role in advancing a more sustainable and circular built environment.

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