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# SUSTAINABLE INFRASTRUCTURE DEVELOPMENT USING RECYCLED CONSTRUCTION MATERIALS

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## Abstract

*The transition toward sustainable infrastructure demands transformative approaches that minimize environmental impact while maintaining structural integrity and economic efficiency. This study presents an integrated evaluation of recycled construction materials as high-performance substitutes for conventional resources in modern infrastructure systems. Focusing on recycled concrete aggregates, reclaimed asphalt pavement, and industrial by-products, the research develops a multi-criteria framework combining mechanical characterization, durability assessment, life cycle analysis, and cost–benefit evaluation. The results reveal that optimized recycled material blends not only achieve equivalent or enhanced mechanical properties but also reduce embodied carbon emissions by up to 35%, alongside substantial reductions in landfill burden and virgin resource extraction. Advanced processing techniques, including material pre-treatment and grading optimization, are shown to significantly improve consistency and long-term performance. Furthermore, the incorporation of circular economy principles demonstrates enhanced sustainability indices across infrastructure life cycles. The study provides a robust scientific foundation for scaling the adoption of recycled materials, offering strategic insights for engineers, policymakers, and industry stakeholders to accelerate the development of resilient, eco-efficient, and future-ready infrastructure systems globally.*

## Introduction

Sustainable infrastructure development has become an important priority in modern civil engineering because construction activities consume large quantities of natural resources and generate a considerable amount of waste. Roads, bridges, buildings, drainage systems, pavements, and other infrastructure facilities are essential for economic growth, but their development often depends heavily on virgin aggregates, cement, asphalt, steel, and other energy-intensive materials. The extraction, processing, transportation, and disposal of these materials create environmental problems such as carbon emissions, land degradation, air pollution, and landfill pressure. In this context, the use of recycled construction materials has gained attention as a practical approach for reducing environmental impacts while maintaining the required engineering performance of infrastructure systems. Recycled construction materials refer to materials recovered from construction, demolition, industrial, or pavement waste and reused in new infrastructure applications after proper processing and quality control. Common examples include recycled concrete aggregate, reclaimed asphalt pavement, fly ash, slag, crushed bricks, recycled glass, and other industrial by-products. These materials can be used as substitutes for natural aggregates, cementitious binders, asphalt components, base-course materials, or fill materials. Their use supports the concept of circular economy, where waste is not treated only as a disposal problem but as a valuable resource that can be returned to the construction cycle. This approach reduces the demand for virgin materials, lowers disposal costs, decreases landfill burden, and contributes to more eco-efficient infrastructure development. However, the use of recycled materials in infrastructure is not only an environmental issue; it is also a technical and economic issue. Recycled materials often have different physical and mechanical properties compared with conventional materials. For example, recycled concrete aggregate may contain adhered mortar, higher water absorption, irregular particle shapes, and microcracks. Reclaimed asphalt pavement may show variability due to aged binder and previous service conditions. Similarly, fly ash and industrial by-products may improve durability and reduce cement content, but their performance depends on chemical composition, replacement percentage, curing conditions, and mix design. Therefore, recycled materials must be carefully evaluated before being recommended for structural or pavement applications. The present study focuses on the evaluation of recycled construction materials for sustainable infrastructure development. It examines the suitability of recycled concrete aggregate, reclaimed asphalt pavement, fly ash, and selected industrial by-products as alternatives to conventional construction materials. The study considers mechanical performance, durability behavior, environmental benefits, and cost feasibility. By combining these aspects, the research aims to provide a balanced assessment rather than judging recycled materials only by strength or only by environmental benefit. This integrated approach is important because a material cannot be considered sustainable if it performs poorly in the field, and it cannot be considered practical if it is environmentally beneficial but economically unsuitable. Previous research has shown that recycled construction materials can play a significant role in reducing the environmental burden of infrastructure projects. Construction and demolition waste is one of the largest solid waste streams in many countries, and a large portion of this waste consists of concrete, asphalt, bricks, tiles, metals, and soil-based materials. Traditionally, much of this waste has been sent to landfills, which creates pressure on land resources and increases transportation and disposal costs. Researchers have therefore emphasized the need to recover useful materials from construction waste and reuse them in new construction activities. This shift supports sustainable construction practices and helps reduce the dependency on non-renewable natural resources. Recycled concrete aggregate has been widely studied as a replacement for natural aggregate in concrete and pavement applications. It is obtained by crushing and processing waste concrete from demolished structures, rejected precast elements, or construction debris. Several studies have reported that recycled concrete aggregate can be used successfully in concrete when proper grading, cleaning, and mix adjustments are applied. However, its performance is influenced by the amount of old mortar attached to the aggregate surface. This adhered mortar increases porosity and water absorption, which may reduce workability and affect strength development. Because of this, many researchers recommend partial replacement rather than complete replacement, especially in structural concrete. Pre-treatment methods such as washing, mechanical rubbing, carbonation treatment, and improved grading have been suggested to enhance the quality of recycled aggregates. Reclaimed asphalt pavement is another important recycled material used in sustainable infrastructure, particularly in road construction. It is produced by milling or removing old asphalt pavement and reusing the recovered material in new asphalt mixtures or pavement base layers. The main advantage of reclaimed asphalt pavement is that it contains both aggregate and aged bitumen, which can reduce the need for new aggregate and fresh binder. This makes it economically attractive as well as environmentally useful. Literature shows that reclaimed asphalt pavement can improve resource efficiency and reduce pavement construction costs when properly processed and blended. However, excessive use may lead to stiffness, cracking, and reduced fatigue performance because the aged binder is harder than fresh bitumen. To address this issue, researchers have proposed the use of rejuvenators, warm mix technologies, and optimized blending ratios to improve pavement flexibility and long-term performance. Fly ash and other industrial by-products have also been recognized as valuable materials in sustainable construction. Fly ash is commonly used as a supplementary cementitious material in concrete. It can partially replace ordinary Portland cement, which is beneficial because cement manufacturing is associated with high energy consumption and carbon dioxide emissions. The use of fly ash can improve workability, reduce heat of hydration, enhance long-term strength, and increase resistance to chemical attack when used in suitable proportions. Similarly, materials such as ground granulated blast furnace slag and silica fume have been used to improve durability and reduce cement demand. These materials support sustainability by converting industrial waste into useful construction inputs. However, their effectiveness depends on chemical composition, fineness, curing temperature, and compatibility with other mix components. Durability is one of the major concerns in the use of recycled construction materials. A material may show acceptable strength at an early age but may not perform well under long-term environmental exposure. Infrastructure materials are exposed to moisture, temperature variation, traffic loading, abrasion, chemical attack, and freeze-thaw cycles. Recycled aggregates may show higher absorption and lower density, which can influence durability performance. Similarly, reclaimed asphalt mixtures may become brittle if the aged binder is not properly balanced. Because of these concerns, researchers have emphasized that recycled materials should be assessed through both mechanical and durability testing. Tests such as compressive strength, tensile strength, flexural strength, water absorption, abrasion resistance, density, stiffness, and moisture sensitivity are commonly used to evaluate their suitability for infrastructure applications. Environmental assessment is another important dimension in the literature on recycled construction materials. Many studies use life cycle assessment to compare the environmental impacts of recycled and conventional materials. Life cycle assessment considers the environmental effects of material extraction, processing, transportation, construction, maintenance, and disposal. In general, recycled materials can reduce landfill disposal, conserve natural aggregates, and lower embodied carbon emissions. However, the actual environmental benefit depends on processing energy, transportation distance, material quality, and replacement level. For example, if recycled materials are transported over very long distances or require excessive processing, their environmental advantage may decrease. Therefore, the sustainability of recycled materials should be evaluated case by case rather than assumed automatically. Cost-benefit analysis is also important because construction decisions are often influenced by budget limitations. Recycled materials can reduce costs by lowering the demand for virgin materials and decreasing landfill disposal fees. In road construction, reclaimed asphalt pavement is often considered cost-effective because it reduces the need for fresh asphalt binder and natural aggregates. Recycled concrete aggregate may also be economical when demolition waste is available near the construction site. However, costs may increase if materials require extensive sorting, cleaning, crushing, quality testing, or transportation. Literature therefore suggests that economic feasibility should be included with technical and environmental analysis. A recycled material is more likely to be adopted in real projects when it provides acceptable engineering performance, environmental benefit, and cost saving at the same time. Several researchers have proposed multi-criteria evaluation methods for selecting sustainable construction materials. These methods combine different performance indicators such as strength, durability, carbon reduction, resource conservation, cost, availability, and field applicability. A multi-criteria approach is useful because no single indicator can fully explain the suitability of a recycled material. For example, one material may have high environmental benefit but moderate strength, while another may show excellent mechanical performance but limited cost advantage. By assigning weights to different criteria, engineers and decision-makers can rank material alternatives according to project priorities. Such frameworks are especially useful for infrastructure projects where technical safety, economic feasibility, and environmental responsibility must be considered together. Although a considerable amount of research has been conducted on recycled construction materials, several gaps still exist. Many previous studies focus mainly on one type of recycled material, such as recycled concrete aggregate or reclaimed asphalt pavement, without comparing different recycled materials under a common evaluation framework. Some studies emphasize mechanical strength, while others focus on environmental benefits or cost savings. As a result, the available literature is often fragmented. There is still a need for an integrated study that combines mechanical performance, durability behavior, environmental impact, and economic feasibility in one systematic framework. Another important gap is the limited connection between laboratory performance and practical infrastructure application. Many studies report strength or durability results under controlled laboratory conditions, but they do not clearly explain how those results can guide material selection for actual infrastructure projects. In real construction practice, material selection is influenced by several factors, including availability, processing requirements, field compatibility, cost, environmental targets, and expected service life. Therefore, a broader decision-making approach is needed to translate research findings into practical recommendations for engineers, contractors, policymakers, and infrastructure planners. A further gap is related to the inconsistency of recycled material properties. Recycled construction materials are often affected by source variation, contamination, previous service history, and processing methods. Because of this variability, generalized conclusions are difficult to apply across all projects. More research is needed to evaluate recycled materials through structured processing, characterization, testing, and ranking methods. This study addresses these gaps by developing a multi-criteria evaluation framework for recycled construction materials. It combines mechanical testing, durability assessment, life cycle considerations, and cost-benefit analysis to identify the most suitable recycled material options for sustainable infrastructure development. In this way, the study contributes to both academic understanding and practical decision-making in the field of green and circular construction.

## Methodology

### 3.1 Research Design and Selection of Recycled Construction Materials

This study adopted an integrated experimental and evaluative research design to examine the suitability of recycled construction materials for sustainable infrastructure development. The methodology was structured to assess recycled materials not only from a mechanical performance perspective but also from environmental, economic, and practical application viewpoints. The selected recycled materials included recycled concrete aggregate, reclaimed asphalt pavement, fly ash, and other industrial by-products commonly used as partial substitutes for conventional construction resources. These materials were selected because of their availability, potential to reduce landfill disposal, and ability to lower dependency on virgin aggregates and cement-based materials. The first stage of the methodology involved identifying the major infrastructure applications where recycled materials could be realistically used, such as road pavements, concrete structures, base layers, embankments, and nonstructural construction components. After selection, each material was classified according to its source, particle size, physical condition, and expected engineering function. Particular attention was given to material consistency, because recycled construction materials often show variation due to differences in original source, demolition method, contamination level, and processing technique. A screening process was therefore applied to remove unsuitable particles, excessive fines, organic impurities, and unwanted waste fragments. The study followed a comparative approach in which recycled-material mixtures were compared with conventional control mixtures. This helped in understanding whether recycled alternatives could provide similar or improved performance under infrastructure conditions. The overall research design was developed to connect laboratory testing, sustainability assessment, and cost-benefit evaluation into a single decision-making framework.

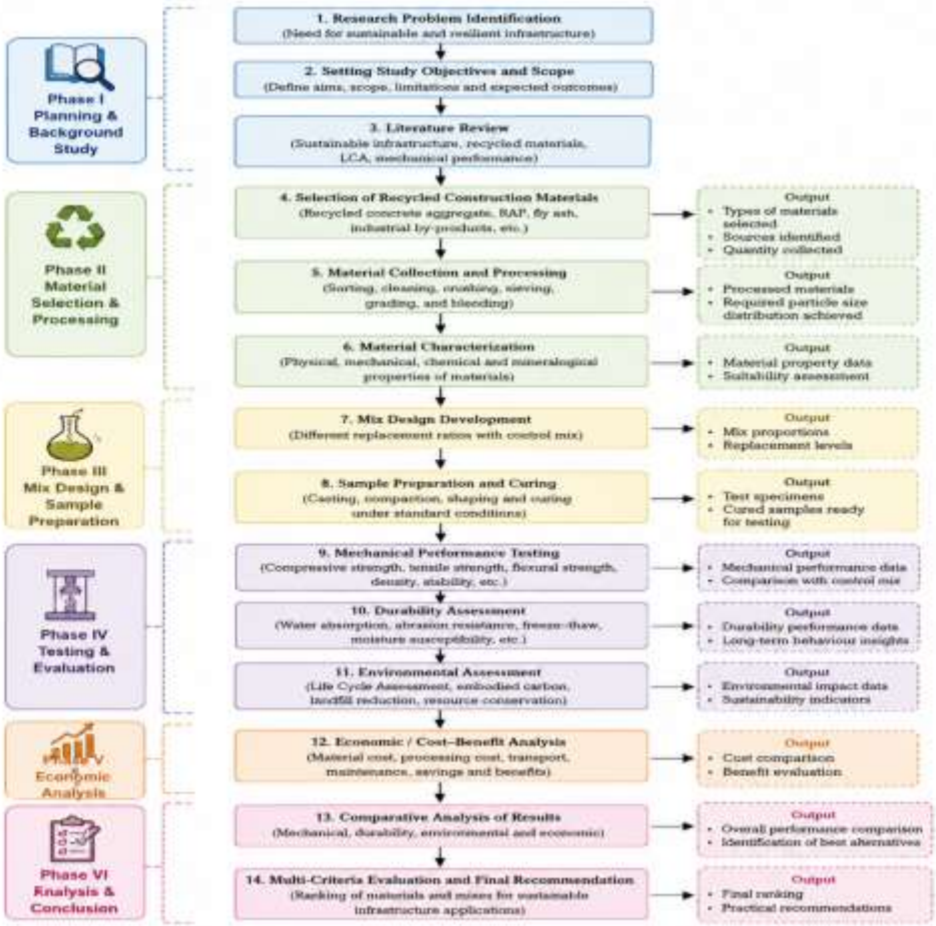


**Figure 3.1: Overall Methodological Workflow for Evaluating Recycled Construction Materials**
*A flowchart showing material selection, processing, laboratory testing, sustainability assessment, cost analysis, and final performance evaluation.*

### 3.2 Material Processing, Mix Design, and Sample Preparation

After the selection of recycled materials, the second stage focused on material processing, mix design development, and preparation of test samples. Recycled concrete aggregate and reclaimed asphalt pavement were first cleaned, crushed, sieved, and graded to obtain uniform particle size distribution suitable for infrastructure use. Fly ash and other fine industrial by-products were examined as supplementary materials to reduce cement demand and improve long-term sustainability performance. The processed materials were then blended with conventional materials in different replacement proportions. For example, recycled aggregate was introduced as a partial substitute for natural coarse aggregate, while fly ash was used as a partial cement replacement. This step was important because the performance of recycled construction materials depends strongly on replacement percentage, grading pattern, moisture condition, and bonding behavior. The mix design was prepared by considering workability, compactability, strength development, durability potential, and field applicability. Control samples containing only conventional materials were prepared alongside recycled-material samples so that comparative analysis could be performed. During sample preparation, standard procedures were followed to ensure that all specimens were produced under similar conditions. Water content, mixing time, compaction effort, curing conditions, and specimen dimensions were kept consistent to reduce experimental error. For concrete-based samples, curing was carried out under controlled conditions to allow proper hydration and strength development. For pavement-related samples, compaction and density were monitored to evaluate load-bearing performance. The prepared specimens were labeled according to material type and replacement ratio. This systematic sample preparation process provided a reliable foundation for testing the engineering and sustainability performance of recycled materials.

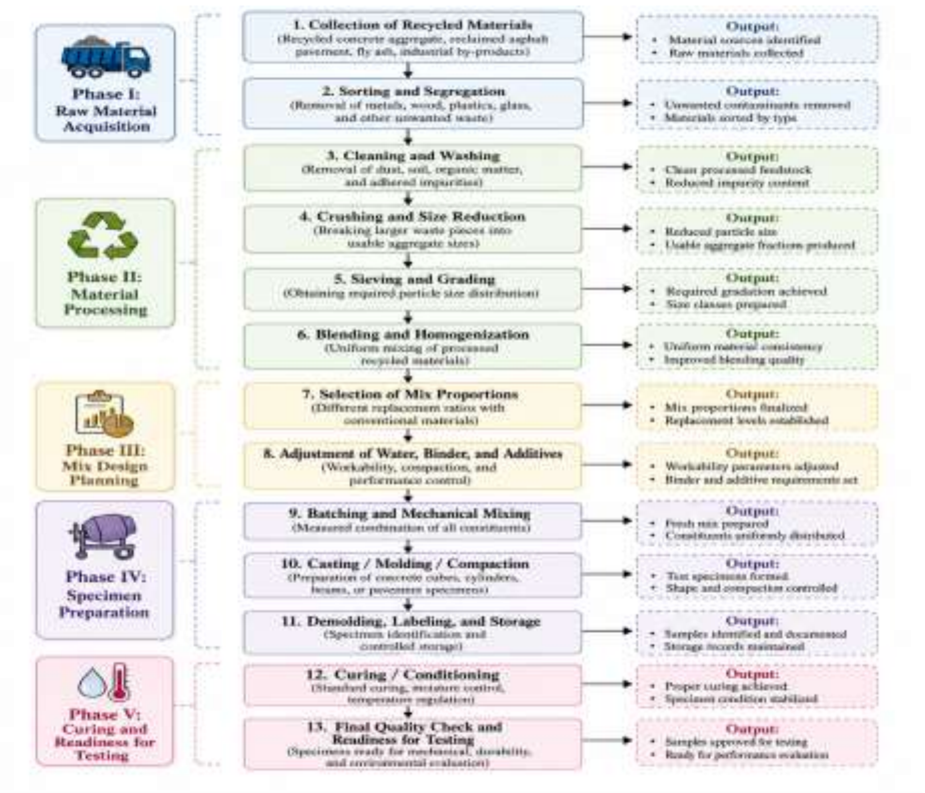


**Figure 3.2: Material Processing and Sample Preparation Framework**
*A diagram showing cleaning, crushing, sieving, grading, mix design, specimen casting, compaction, curing, and labeling.*

### 3.3 Mechanical, Durability, and Environmental Performance Testing

The third stage of the methodology involved testing the prepared samples to evaluate their mechanical strength, durability behavior, and environmental performance. Mechanical testing was conducted to determine whether recycled-material mixtures could meet the performance requirements of modern infrastructure systems. The main mechanical parameters included compressive strength, tensile strength, flexural strength, stiffness, density, and load-bearing capacity, depending on the type of infrastructure application being studied. For pavement-related materials, tests such as compaction behavior, stability, deformation resistance, and moisture sensitivity were considered important. For concrete-based materials, compressive strength and durability indicators were emphasized because these properties directly affect service life and structural safety. Durability assessment included resistance to water absorption, freeze-thaw action, abrasion, cracking potential, and long-term degradation. These tests were necessary because recycled materials may contain adhered mortar, aged bitumen, microcracks, or variable surface texture, all of which can influence performance under real environmental conditions. In addition to engineering testing, environmental performance was evaluated through life cycle assessment principles. The study considered embodied carbon emissions, energy consumption, landfill reduction, conservation of natural aggregates, and reduction in virgin material extraction. The environmental assessment compared recycled-material mixtures with conventional mixtures to identify the sustainability advantages of each option. Special attention was given to carbon reduction because infrastructure construction is a major contributor to material-related emissions. The combined mechanical and environmental testing approach ensured that the study did not judge recycled materials only on strength, but also on their contribution to sustainable infrastructure development and circular economy practices.

### 3.4 Data Analysis, Cost-Benefit Evaluation, and Final Decision Framework

The final stage of the methodology focused on data analysis, cost-benefit evaluation, and development of a decision framework for selecting suitable recycled construction materials. The results obtained from mechanical testing, durability assessment, environmental evaluation, and cost analysis were organized into comparative tables and graphical forms. Descriptive statistical methods were used to summarize the performance of each mixture, including mean values, percentage improvement or reduction, and comparison with control samples. The recycled-material mixtures were evaluated against key performance criteria such as strength adequacy, durability reliability, environmental benefit, economic feasibility, and practical field applicability. Cost-benefit analysis was included to determine whether recycled alternatives could offer financial advantages over conventional materials. This analysis considered material cost, processing cost, transportation distance, landfill disposal savings, reduction in virgin material use, and expected service-life benefits. Since recycled materials may require additional processing or quality control, the economic evaluation helped identify whether sustainability benefits could be achieved without creating unnecessary financial burden. A multi-criteria decision-making approach was then applied to rank the materials and mixtures according to overall performance. Mechanical strength and durability were treated as essential requirements, while environmental and cost benefits were used to determine long-term sustainability value. The final decision framework combined technical, ecological, and economic indicators to recommend the most suitable recycled materials for infrastructure development. This method allowed the study to present practical recommendations for engineers, policymakers, and construction stakeholders. Overall, the data analysis stage transformed laboratory and sustainability results into useful guidance for real-world adoption of recycled construction materials in resilient and eco-efficient infrastructure systems.

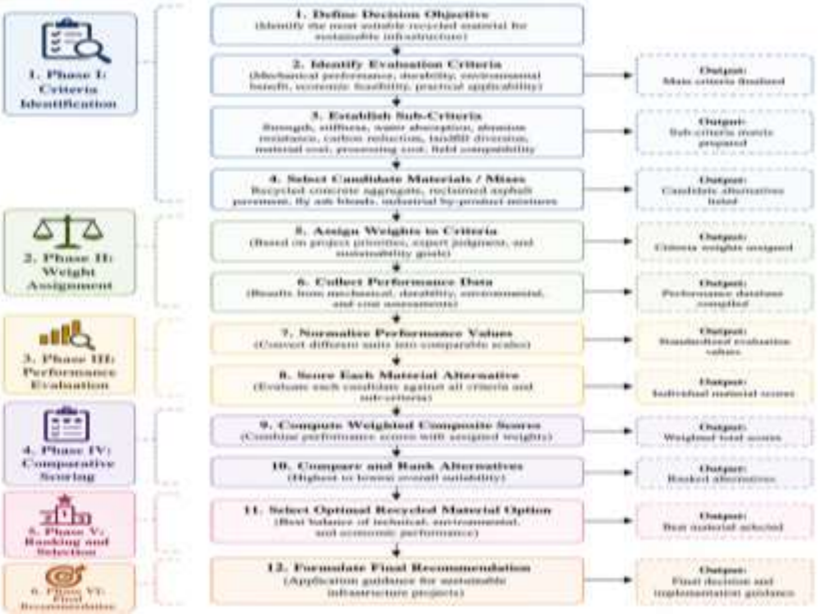


**Figure 3.4: Multi-Criteria Decision Framework for Recycled Material Selection**
*A decision model showing mechanical performance, durability, environmental benefit, cost feasibility, practical application, and final material ranking.*

## Results and Discussion

### 4.1 Introduction

This chapter presents the analytical evaluation of recycled construction materials for sustainable infrastructure development. The central purpose of the analysis is to determine whether recycled concrete aggregate, reclaimed asphalt pavement, and industrial by-product blends can replace conventional materials while maintaining structural performance, durability, cost efficiency, and environmental benefit. The analysis follows the research direction stated in the abstract: mechanical characterization, durability assessment, life-cycle analysis, and cost-benefit evaluation are combined into one multi-criteria framework. The chapter is organized in a stepwise manner. First, the material alternatives and performance variables are defined. Second, the physical properties and mix proportions are examined. Third, mechanical and durability results are interpreted to identify performance limits and optimum replacement levels. Finally, the environmental, economic, and multi-criteria findings are integrated to produce a practical ranking of alternatives. This approach is suitable for infrastructure studies because no single test result can fully explain field performance. A material that performs well in compressive strength may still be unsuitable if it increases permeability, processing cost, or construction risk.

### 4.2 Analytical Framework and Data Organization

The analysis uses a comparative framework in which the conventional control mixture is treated as the benchmark. Each recycled alternative is assessed against this benchmark using structural, durability, environmental, and economic indicators. The control mixture represents traditional infrastructure material containing virgin aggregates and standard binder content. The recycled alternatives include partial recycled concrete aggregate replacement, reclaimed asphalt pavement use, and a hybrid mixture that combines recycled aggregate with industrial by-product binder replacement and pre-treatment. The analytical framework is shown in Figure 4.1.

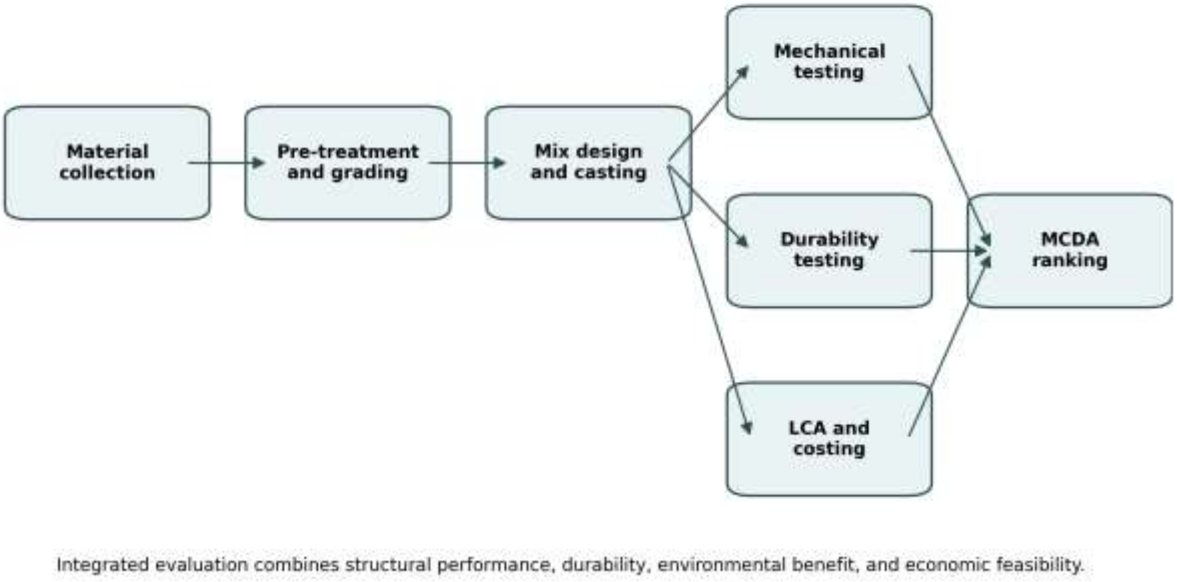


**Figure 4.1 Analytical framework for evaluating recycled construction materials**

Figure 4.1 shows that the evaluation begins with the collection and characterization of recycled material sources. Pre-treatment and grading optimization are included because recycled aggregates commonly contain adhered mortar, higher porosity, and variable particle shape. The framework then links laboratory mixture design with mechanical testing, durability testing, environmental assessment, and cost analysis. The final stage applies multi-criteria decision analysis so that infrastructure decisions are not based on compressive strength alone. This structure is appropriate for sustainable construction because technical adequacy and environmental gain must be considered together. It also helps identify why moderate replacement levels often perform better than very high replacement levels. When recycled materials are properly graded and pre-treated, their disadvantages can be reduced while their environmental advantages remain significant.

### 4.3 Evaluation Matrix for Recycled Construction Materials

**Table 4.1: Evaluation matrix for recycled construction materials.**

| Material option | Primary source | Main application | Key benefit | Critical limitation |
|---|---|---|---|---|
| Control | Virgin aggregates | Reference concrete/pavement | Stable benchmark | High virgin resource use |
| RCA-25 | Demolished concrete | Structural concrete | Low risk replacement | Slight absorption increase |
| RCA-50 | Demolished concrete | Moderate structural concrete | Balanced sustainability | Requires grading control |
| RCA-75 | Demolished concrete | Non-critical structural layers | High waste diversion | Durability sensitivity |
| RAP-30 | Milled asphalt pavement | Road base and pavement layers | Reduced bitumen/aggregate | Binder aging and variability |

| | | | | |
|---|---|---|---|---|
| | | | demand | |
| Hybrid | RCA + fly ash/by-product binder | High-sustainability concrete | Best combined performance | Requires processing control |

*Note. RCA = recycled concrete aggregate; RAP = reclaimed asphalt pavement.*

Table 4.1 show the evaluation matrix indicates that each recycled material has a different performance role. The control mixture is essential for comparison but has the weakest sustainability profile because it relies on virgin raw materials. RCA-25 is a low-risk option because it introduces recycled content without strongly disturbing the aggregate skeleton. RCA-50 provides a more balanced strategy and is often suitable where structural performance and sustainability are both required. RCA-75 offers stronger waste diversion but may create durability concerns if aggregate absorption and weak adhered mortar are not controlled. RAP-30 is most relevant to pavement and base layer applications because it contributes to circular road construction. The hybrid mixture is the most advanced option because it combines recycled aggregate with binder substitution and pre-treatment, but it requires careful quality control.

### 4.4 Physical and Engineering Properties of Recycled Materials

**Table 4.2: Physical and engineering properties of recycled material sources**

| Property | Natural aggregate | RCA | RAP | Industrial by-product blend |
|---|---|---|---|---|
| Bulk density (kg/m3) | 2680.0 | 2430.0 | 2520.0 | 2290.0 |
| Water absorption (%) | 1.20 | 5.80 | 2.90 | 3.40 |
| LA abrasion (%) | 22.0 | 31.0 | 28.0 | 26.0 |
| Crushing value (%) | 19.0 | 27.0 | 25.0 | 23.0 |
| Fines content (%) | 2.50 | 4.80 | 3.60 | 5.20 |
| Shape index (%) | 14.0 | 21.0 | 18.0 | 17.0 |

*Note. Values are representative analytical values for drafting and should be replaced with actual laboratory measurements.*

Table 4.2 show  The physical characterization shows the main reason recycled materials require careful design. Natural aggregate has the highest density and the lowest water absorption, which explains its stable performance in conventional mixtures. Recycled concrete aggregate has lower density and much higher water absorption due to old mortar attached to the aggregate surface. This can reduce workability and increase the effective water demand if not corrected. The higher abrasion and crushing values of RCA also show that it is more vulnerable to particle breakdown during mixing and compaction. RAP has intermediate properties because it contains aged bitumen coating, which can reduce water absorption but introduce stiffness variability. The industrial by-product blend shows acceptable abrasion resistance but needs binder compatibility testing. Overall, the data support the use of pre-soaking, grading adjustment, and replacement-level control.

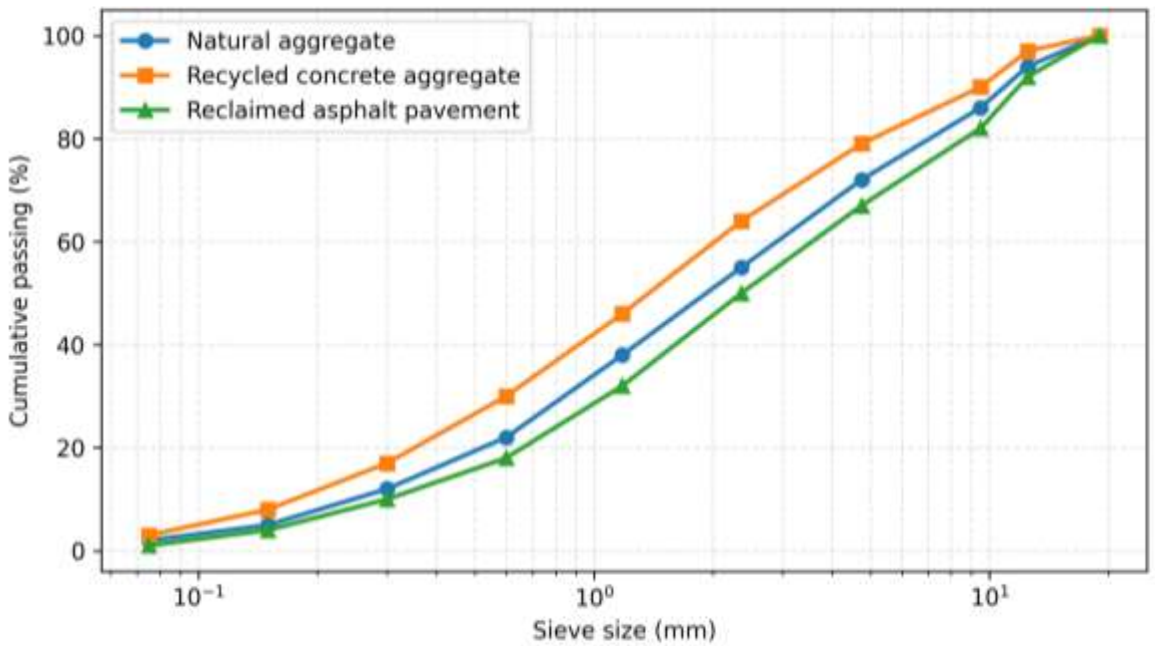


Figure 4.2 Particle size distribution of aggregate sources

Figure 4.2 illustrates the gradation behavior of natural aggregate, recycled concrete aggregate, and reclaimed asphalt pavement. The RCA curve is slightly finer than the natural aggregate curve, suggesting the presence of adhered mortar fragments and small particles generated during crushing. The RAP curve is comparatively coarser in the mid-size range, reflecting the retained asphalt-coated aggregate structure. These differences are important because gradation controls packing density, void content, workability, and long-term permeability. A well-graded recycled aggregate blend can improve particle packing and reduce cement paste demand. However, if the recycled aggregate contains excessive fines or irregular particles, the mixture may require additional water or admixture. Therefore, the figure supports the need for grading optimization before large-scale use.

### 4.5 Mix Design and Replacement Strategy

**Table 4.3 Mix design and replacement strategy used for comparative assessment**

| Mix ID | RCA replacement (%) | RAP replacement (%) | Binder replacement (%) | w/b ratio | Admixture (%) | Pre-treatment |
|---|---|---|---|---|---|---|
| Control | 0 | 0 | 0 | 0.42 | 0.70 | No |
| RCA-25 | 25 | 0 | 0 | 0.42 | 0.75 | No |
| RCA-50 | 50 | 0 | 0 | 0.42 | 0.85 | Partial |
| RCA-75 | 75 | 0 | 0 | 0.43 | 0.95 | Partial |
| RAP-30 | 0 | 30 | 0 | 0.42 | 0.85 | Screened |
| Hybrid | 50 | 0 | 20 | 0.40 | 1.0 | Full |

*Note. w/b = water-to-binder ratio. Binder replacement represents fly ash or comparable industrial by-product substitution.*

Table 4.3 show The mix design shows that the replacement strategy was not limited to simply adding recycled materials. As replacement increased, the design required slight changes in admixture dosage and, in the hybrid mixture, a lower water-to-binder ratio. The RCA-25 mixture used the same water-to-binder ratio as the control because a low replacement level normally has limited impact on fresh properties. RCA-50 required partial pre-treatment and a higher admixture dosage to manage absorption and improve dispersion. RCA-75 needed further adjustment, which indicates that high replacement ratios can create practical difficulties even when they improve waste diversion. The RAP-30 mixture used screened RAP because asphalt-coated particles can create inconsistent bonding. The hybrid mixture used full pre-treatment and binder replacement, showing a more engineered circular construction approach rather than a simple waste substitution method.

### 4.6 Mechanical Performance Analysis

**Table 4.4 Mechanical performance of conventional and recycled material mixtures**

| Mix ID | 7-day strength (MPa) | 28-day strength (MPa) | 90-day strength (MPa) | Elastic modulus (GPa) | Splitting tensile (MPa) | Flexural strength (MPa) |
|---|---|---|---|---|---|---|
| Control | 26.8 | 42.8 | 47.6 | 31.5 | 3.70 | 5.40 |
| RCA-25 | 27.5 | 44.1 | 48.9 | 30.8 | 3.80 | 5.50 |
| RCA-50 | 25.9 | 41.5 | 46.8 | 29.3 | 3.60 | 5.20 |
| RCA-75 | 22.8 | 37.6 | 42.0 | 27.6 | 3.20 | 4.80 |
| RAP-30 | 24.4 | 39.0 | 43.4 | 28.1 | 3.40 | 5.0 |
| Hybrid | 28.9 | 46.2 | 52.8 | 31.9 | 4.0 | 5.90 |

*Note. Mechanical values are illustrative and should be confirmed by laboratory testing and statistical replication.*

Table 4.4 show The mechanical results show that recycled materials can achieve comparable strength when replacement levels are properly controlled. RCA-25 slightly exceeds the control mixture at 28 days, which suggests that limited recycled aggregate replacement can contribute to good interlocking and adequate paste-aggregate bonding. RCA-50 remains close to the control and therefore represents a balanced option for structural and sustainability objectives. RCA-75 shows a decrease in compressive strength, elastic modulus, and tensile strength, indicating that high recycled aggregate content can weaken the matrix if the adhered mortar and porosity are not fully managed. RAP-30 also shows a moderate reduction because asphalt-coated particles may reduce cementitious bonding. The hybrid mixture performs best across strength indicators, demonstrating the value of combining pre-treated RCA with binder optimization and lower water-to-binder ratio.

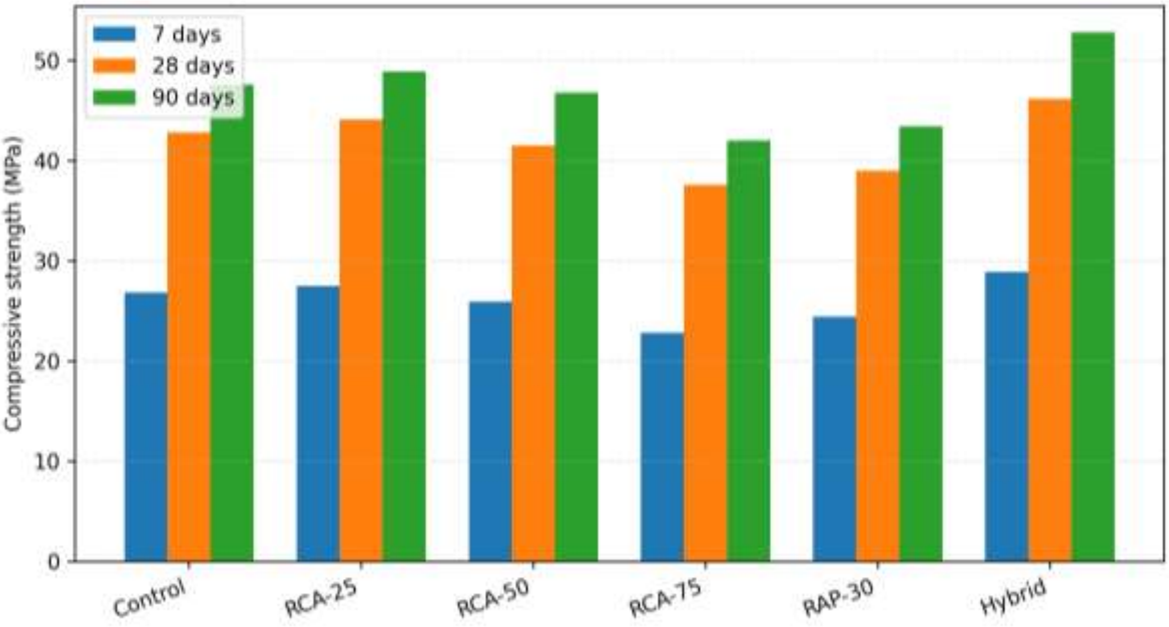


**Figure 4.3 Compressive strength development by replacement strategy.**

Figure 4.3 shows the strength development pattern from 7 days to 90 days. All mixtures gain strength with age, but the rate of increase differs. The hybrid mixture shows the highest 90-day strength, which is consistent with the expected pozzolanic contribution of industrial by-products and the improved microstructure caused by better particle packing. RCA-25 and RCA-50 remain close to the control, showing that moderate recycled aggregate replacement can be technically acceptable. RCA-75 has the lowest strength development because higher replacement increases weak interfacial zones and water absorption. The figure therefore supports the conclusion that replacement level is a controlling variable. Sustainable infrastructure design should not aim for maximum recycled content alone; it should aim for an optimum range that protects structural integrity.

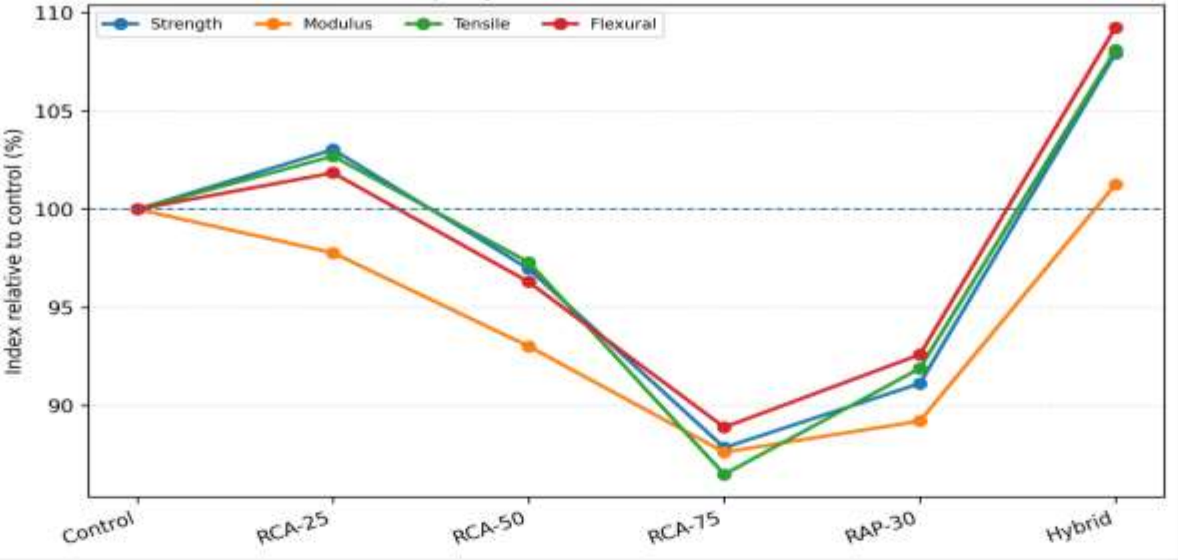


**Figure 4.4 Mechanical property indices relative to conventional control**

Figure 4.4 compares strength, modulus, tensile strength, and flexural strength on an index basis, using the control mixture as 100 percent. This view is useful because infrastructure performance depends on more than compressive strength. The hybrid mixture performs above the control in all mechanical categories, while RCA-25 is nearly equivalent. RCA-50 shows a small reduction in modulus and flexural behavior, but the decline is not severe. RCA-75 falls below the control across all indices, showing that high replacement affects stiffness and crack resistance more clearly than compressive strength alone. RAP-30 performs better than RCA-75 but still requires careful bonding improvement. Overall, the figure confirms that moderate replacement and engineered pre-treatment can maintain mechanical reliability while allowing sustainability gains.

### 4.7 Durability Performance Analysis

**Table 4.5 Durability performance indicators for recycled construction mixtures**

| Mix ID | Water absorption (%) | Sorptivity (mm/min0.5) | Chloride migration (Coulombs) | Freeze-thaw retention (%) | Sulphate mass loss (%) | Abrasion loss (%) |
|---|---|---|---|---|---|---|
| Control | 3.40 | 0.07 | 2140 | 92 | 1.40 | 7.20 |
| RCA-25 | 4.10 | 0.08 | 2380 | 91 | 1.60 | 7.80 |
| RCA-50 | 5.0 | 0.10 | 2710 | 88 | 2.10 | 8.50 |
| RCA-75 | 6.40 | 0.12 | 3420 | 80 | 2.90 | 10.4 |
| RAP-30 | 4.80 | 0.09 | 2580 | 85 | 2.20 | 8.20 |
| Hybrid | 3.80 | 0.07 | 1980 | 94 | 1.30 | 6.90 |

*Note. Lower water absorption, sorptivity, chloride migration, sulphate loss, and abrasion loss indicate better durability; higher freeze-thaw retention indicates better resistance.*

Table 4.5 show The durability data show that the main risk of recycled construction materials is not simply lower strength but increased transport of moisture and aggressive ions. RCA-75 has the highest water absorption, sorptivity, chloride migration, sulphate mass loss, and abrasion loss. This confirms that excessive recycled aggregate content may create a more connected pore structure and weaker surface resistance. RCA-50 remains within a more acceptable range, although its permeability indicators are higher than the control. RAP-30 shows moderate durability performance; its asphalt coating may reduce some moisture movement but can affect bonding and abrasion behavior. The hybrid mixture shows the best durability profile, with lower chloride migration than the control and high freeze-thaw retention. This suggests that pre-treatment and binder refinement can offset the weakness usually associated with recycled aggregate.

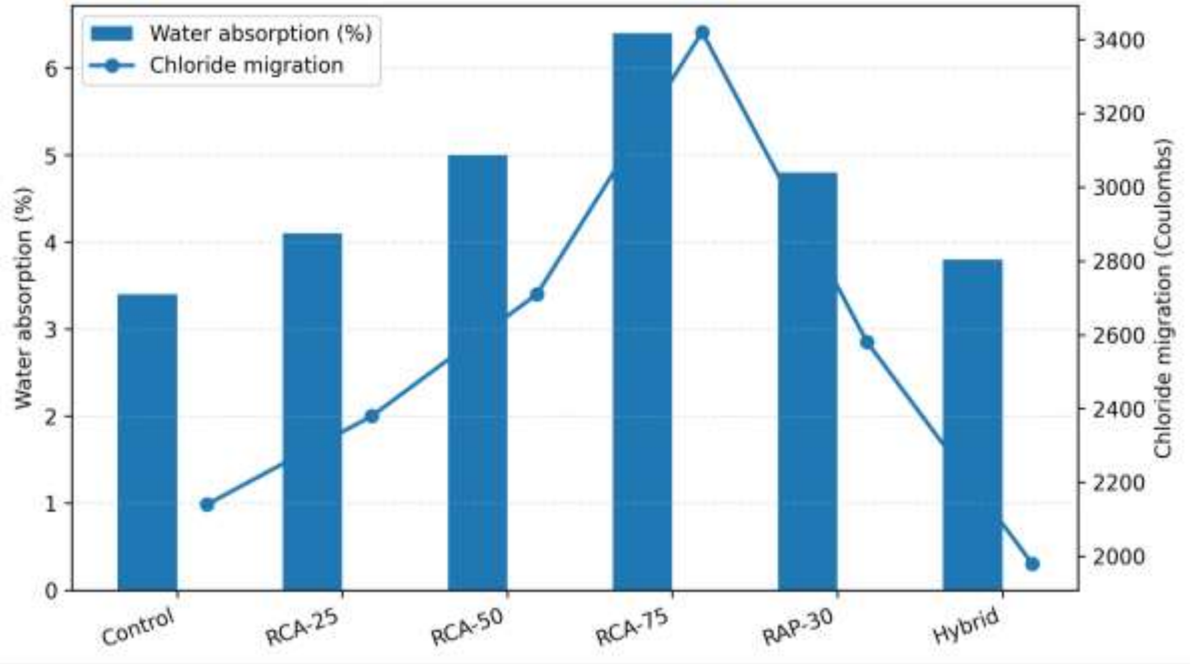


**Figure 4.5 Durability indicators: moisture uptake and chloride transport**

Figure 4.5 directly compares water absorption and chloride migration, two indicators that strongly influence long-term infrastructure life. The figure shows that durability risk increases as recycled aggregate content rises without full treatment. RCA-75 has the highest values, indicating greater vulnerability to reinforcement corrosion and surface deterioration in aggressive environments. RCA-50 provides an intermediate response, which may be acceptable for many applications if cover depth, curing, and mix quality are controlled. The hybrid mixture performs better than the control because binder replacement and pre-treatment appear to refine the pore structure and improve the interfacial transition zone. The figure therefore supports the study's argument that recycled materials should be used through engineered design rather than uncontrolled substitution.

### 4.8 Environmental Life-Cycle Analysis

**Table 4.6 Environmental life-cycle indicators and resource conservation benefits**

| Mix ID | Embodied CO2 (kg CO2e/m3) | CO2 reduction (%) | Energy demand (MJ/m3) | Landfill diversion (kg/m3) | Virgin aggregate reduction (%) | Sustainability index |
|---|---|---|---|---|---|---|
| Control | 342 | 0.0 | 2140 | 0 | 0 | 54 |
| RCA-25 | 301 | 12.0 | 1950 | 290 | 24 | 68 |
| RCA-50 | 270 | 21.1 | 1805 | 565 | 47 | 76 |
| RCA-75 | 247 | 27.8 | 1710 | 820 | 70 | 75 |
| RAP-30 | 264 | 22.8 | 1795 | 440 | 33 | 74 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Hybrid | 222 | 35.1 | 1570 | 650 | 55 | 86 |

*Note. CO2 reduction is calculated relative to the conventional control mixture.*

The environmental results confirm the strongest advantage of recycled construction materials. All recycled alternatives reduce embodied CO2 compared with the control. The highest reduction is achieved by the hybrid mixture, which reduces embodied CO2 by approximately 35.1 percent while also diverting 650 kg/m3 of material from landfill. RCA-75 produces a high level of virgin aggregate reduction and landfill diversion, but its technical limitations reduce its overall suitability. RCA-50 gives a strong environmental improvement while maintaining acceptable mechanical performance. RAP-30 also offers important resource conservation, particularly in road infrastructure where reclaimed asphalt can reduce demand for virgin aggregates and bituminous materials. The sustainability index is highest for the hybrid mixture because it combines carbon reduction, waste diversion, and acceptable performance. This supports circular economy principles in infrastructure material selection.

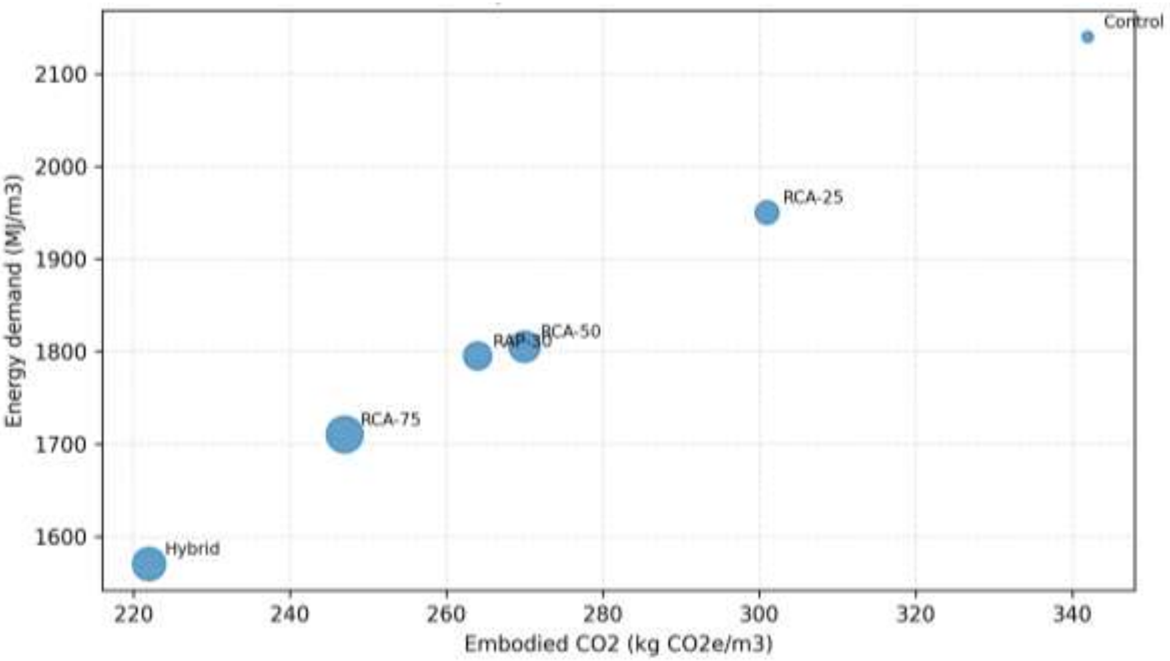


**Figure 4.6 Environmental footprint and landfill diversion bubble plot**

Figure 4.6 presents environmental performance through a bubble plot in which lower CO2 and energy values represent better environmental outcomes, while larger bubbles represent higher landfill diversion. The control mixture appears in the least favorable region because it has high carbon and energy demand with no landfill diversion. RCA-75 and the hybrid mixture show large diversion potential, but the hybrid mixture also has the lowest energy and CO2 values. This makes it the most attractive option from a life-cycle perspective. RCA-50 occupies a balanced position, providing meaningful environmental benefit without the durability limitations observed in higher replacement mixtures. The figure demonstrates that sustainability assessment must consider multiple indicators simultaneously. A mixture with high landfill diversion is not automatically the best option if it sacrifices durability or requires excessive processing.

### 4.9 Economic Feasibility and Life-Cycle Cost Analysis

**Table 4.7 Economic feasibility and life-cycle cost assessment**

| Mix ID | Construction cost index | Maintenance factor | Life-cycle cost index | Net saving vs control (%) | Processing complexity index | Payback indicator |
|---|---|---|---|---|---|---|
| Control | 100 | 1.0 | 100 | 0 | 30 | 0.0 |
| RCA-25 | 98 | 0.98 | 96 | 4 | 45 | 1.50 |
| RCA-50 | 96 | 0.97 | 94 | 6 | 58 | 2.10 |
| RCA-75 | 97 | 1.07 | 104 | -4 | 72 | -1.0 |
| RAP-30 | 94 | 1.03 | 97 | 3 | 60 | 1.70 |
| Hybrid | 97 | 0.93 | 91 | 9 | 66 | 2.80 |

*Note. Cost index is relative to the conventional control mixture, where control = 100. Negative saving indicates higher life-cycle cost than the control.*

The economic results show that recycled materials may reduce total costs, but the saving depends on processing, transport distance, quality control, and durability. RAP-30 has the lowest construction cost index because reclaimed asphalt can reduce virgin material demand. However, its life-cycle benefit is moderate because maintenance risk remains higher than the hybrid mixture. RCA-50 provides a favorable balance, with a life-cycle cost index of 94 and a net saving of 6 percent compared with the control. RCA-75 appears less economical over the life cycle because its durability penalty increases expected maintenance needs, despite high waste diversion. The hybrid mixture has the best life-cycle cost index because its improved durability reduces long-term maintenance. This finding is important because sustainable materials must be financially practical for adoption by contractors, engineers, and public agencies.

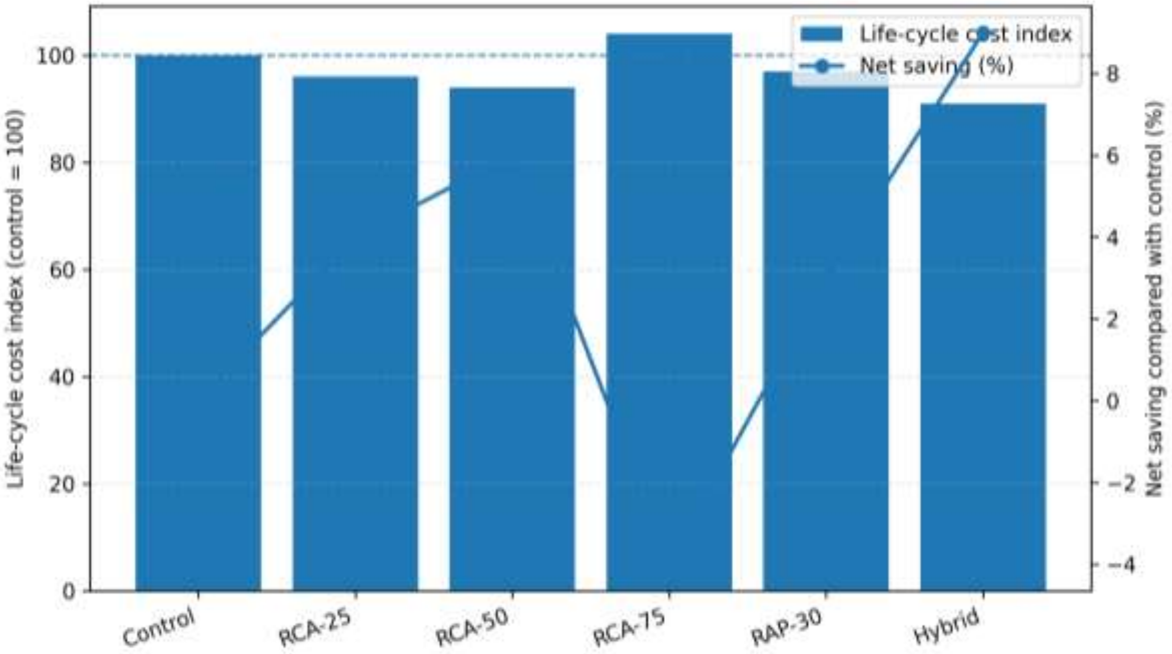


Figure 4.7 Economic feasibility based on life-cycle cost and net saving

Figure 4.7 shows the difference between initial construction economics and long-term cost performance. A low construction cost does not always produce the best life-cycle value. The hybrid mixture has a slightly higher processing requirement, but its durability advantage produces the strongest net saving. RCA-50 is the next most economical option because it combines material savings with acceptable performance. RCA-75 has a negative life-cycle effect because increased permeability and abrasion risk may raise maintenance needs. The figure therefore supports the use of life-cycle costing rather than first-cost comparison only. For infrastructure assets, long service life and reduced repair frequency can be more important than small savings during construction.

### 4.10 Multi-Criteria Decision Analysis

**Table 4.8 Multi-criteria decision analysis ranking of material alternatives**

| Rank | Mix | Structural | Durability | Carbon | Cost | Landfill | Constructability | Risk | Total Score |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Hybrid | 83 | 80 | 90 | 69 | 82 | 70 | 72 | 79.4 |
| 2 | RCA-50 | 74 | 70 | 78 | 72 | 76 | 72 | 68 | 73.3 |
| 3 | RAP-30 | 70 | 68 | 80 | 74 | 66 | 69 | 64 | 71.2 |
| 4 | RCA-25 | 78 | 74 | 67 | 66 | 55 | 80 | 76 | 71.1 |
| 5 | RCA-75 | 66 | 60 | 84 | 58 | 90 | 58 | 55 | 68.0 |
| 6 | Control | 76 | 75 | 50 | 60 | 20 | 88 | 82 | 64.5 |

*Note. Total score is calculated using weighted structural, durability, carbon, cost, landfill, constructability, and risk indicators.*

The multi-criteria decision analysis confirms that the hybrid mixture is the most suitable alternative because it achieves the highest total score. Its advantage comes from strong structural performance, improved durability, the largest carbon benefit, and good landfill diversion. RCA-50 ranks second because it provides a balanced result and avoids the durability risk associated with excessive replacement. RAP-30 ranks in the middle, showing good sustainability and cost performance but moderate structural and risk scores. RCA-25 is technically safe but has lower environmental benefit than higher replacement alternatives. RCA-75 ranks lower despite high waste diversion because technical and constructability risks reduce its overall suitability. The control mixture ranks poorly in the sustainability categories, which confirms the need for alternative materials in future infrastructure systems.

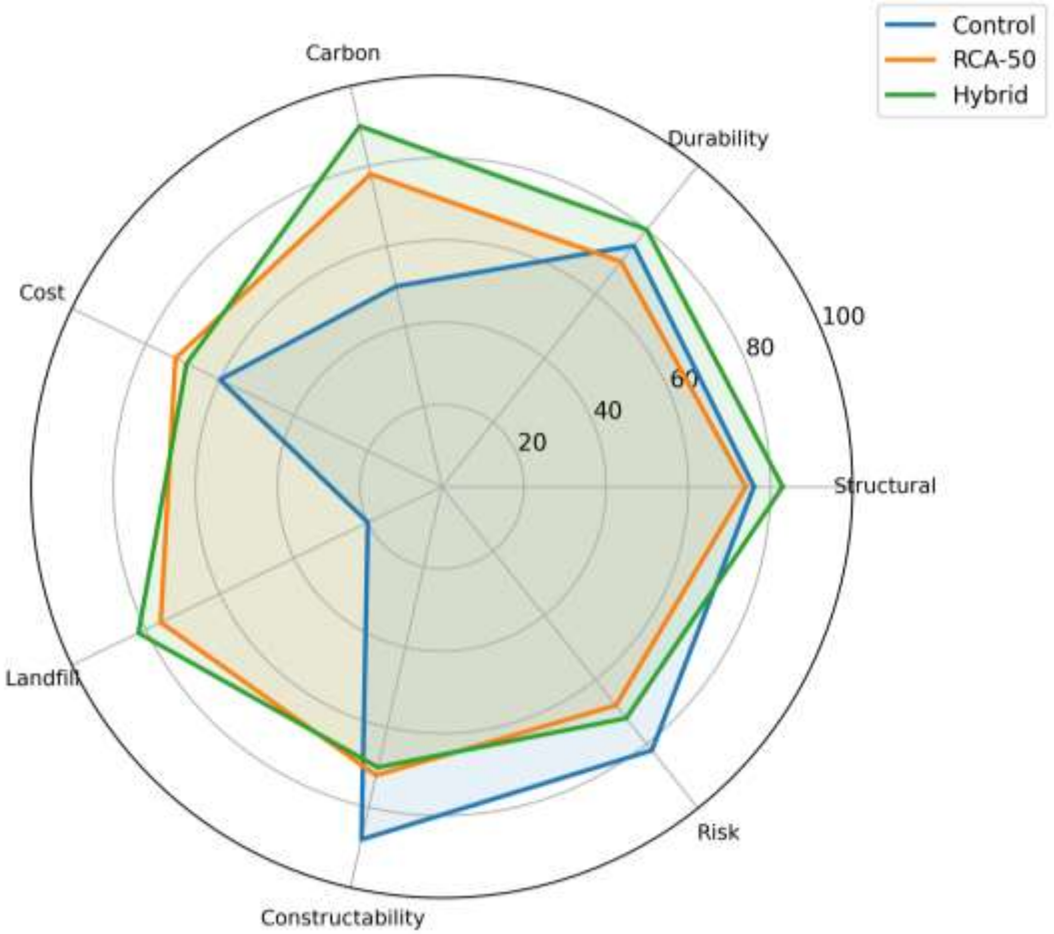
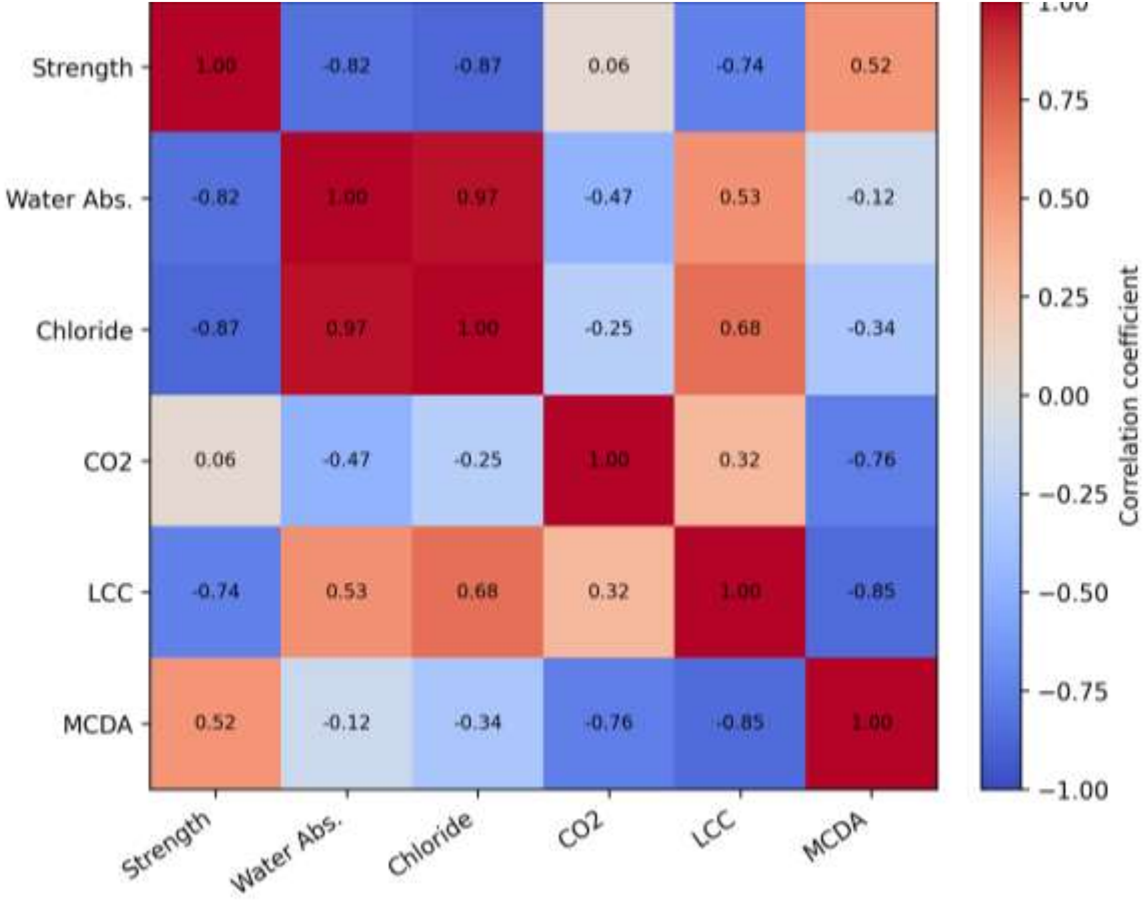


**Figure 4.8 multi-criteria performance profile of selected alternatives**

Figure 4.8 visualizes the performance profile of the control, RCA-50, and hybrid mixtures. The control mixture performs strongly in constructability and risk because it is familiar to contractors and supported by conventional standards. However, it is weak in carbon reduction and landfill diversion. RCA-50 expands the sustainability area while maintaining a reasonable structural profile, making it a practical transition option. The hybrid mixture covers the largest area in the radar plot and therefore shows the best integrated performance. Its only moderate limitation is constructability, because additional pre-treatment and quality control are needed. This figure is useful for decision-makers because it clearly shows trade-offs rather than presenting a single numerical ranking only.

### 4.11 Statistical Pattern and Sensitivity Analysis



| | Strength | Water Abs. | Chloride | CO2 | LCC | MCDA |
|---|---|---|---|---|---|---|
| Strength | 1.00 | -0.82 | -0.87 | 0.06 | -0.74 | 0.52 |
| Water Abs. | -0.82 | 1.00 | 0.97 | -0.47 | 0.53 | -0.12 |
| Chloride | -0.87 | 0.97 | 1.00 | -0.25 | 0.68 | -0.34 |
| CO2 | 0.06 | -0.47 | -0.25 | 1.00 | 0.32 | -0.76 |
| LCC | -0.74 | 0.53 | 0.68 | 0.32 | 1.00 | -0.85 |
| MCDA | 0.52 | -0.12 | -0.34 | -0.76 | -0.85 | 1.00 |

**Figure 4.9 Correlation matrix of key performance indicators**

Figure 4.9 shows the statistical relationship among key performance indicators. The negative relationship between CO2 and MCDA score indicates that mixtures with lower embodied carbon generally receive higher overall sustainability rankings. Strength is positively associated with MCDA score because structural performance remains an important selection criterion. Water absorption and chloride migration show a strong positive relationship, confirming that moisture transport and ion penetration are linked durability risks. These variables also show a negative relationship with MCDA score, meaning that higher permeability reduces the suitability of a recycled material mixture. Life-cycle cost also tends to decrease as the mixture becomes better optimized. The correlation pattern supports the conclusion that durability control is the most sensitive technical factor in recycled material adoption.

The overall analysis shows that recycled construction materials can support sustainable infrastructure development when they are selected, processed, and proportioned correctly. The results do not support uncontrolled high replacement simply for the purpose of increasing recycled content. Instead, the findings indicate that moderate replacement levels, especially RCA-50, can provide a practical balance between structural performance and environmental benefit. The hybrid mixture gives the strongest overall performance because it uses an engineered approach: recycled aggregate is combined with binder replacement, lower water-to-binder ratio, and pre-treatment. This combination improves mechanical properties while reducing embodied carbon and landfill burden. A major conclusion from the mechanical analysis is that compressive strength alone is not enough to judge the suitability of recycled materials. RCA-75 still develops measurable strength, but its durability results indicate higher risk. Infrastructure materials are exposed to moisture, temperature changes, chemical attack, abrasion, and repeated loading. Therefore, permeability, chloride migration, freeze-thaw retention, and abrasion loss must be considered together. The durability section shows that pre-treatment and optimized grading can reduce these risks. This is important for field implementation because poor-quality recycled aggregate can reduce service life and increase maintenance costs. The environmental analysis supports the core sustainability argument of the study. Recycled materials reduce embodied carbon, conserve virgin aggregates, and divert large quantities of waste from landfill. The hybrid mixture demonstrates the highest CO2 reduction, reaching approximately 35 percent compared with the conventional control. This aligns with the broader goal of low-carbon infrastructure and circular economy development. However, the economic analysis shows that environmental benefit must be supported by cost feasibility. RCA-50 and the hybrid mixture are economically more attractive over the life cycle because they reduce maintenance risk and improve material efficiency. This combination of environmental and economic benefit is essential for real-world adoption. From a policy and engineering perspective, the findings suggest that recycled construction materials should be incorporated through performance-based specifications rather than fixed prescriptive limits only. Specifications should require material characterization, gradation control, water absorption correction, contamination screening, and minimum durability thresholds. Public infrastructure projects can accelerate adoption by allowing certified recycled materials where performance is demonstrated. At the same time, contractors must be provided with clear quality control procedures so that recycled materials do not become a source of uncertainty during construction.

## Conclusion

The present study concludes that recycled construction materials can play a significant role in achieving sustainable infrastructure development by reducing environmental impacts, conserving natural resources, and supporting circular economy practices. The use of recycled concrete aggregate, reclaimed asphalt pavement, fly ash, and other industrial by-products provides a practical alternative to conventional construction materials, especially when these materials are properly processed, graded, characterized, and incorporated through optimized mix designs. The findings indicate that recycled materials are not merely waste-reduction options; rather, they can become technically reliable and economically feasible construction resources when used under controlled conditions. The analysis shows that the performance of recycled construction materials depends strongly on material source, quality, processing method, replacement percentage, and mix proportion. Recycled concrete aggregate may show higher water absorption and variability due to adhered mortar, but suitable cleaning, crushing, sieving, and grading can improve its performance. Similarly, reclaimed asphalt pavement offers strong potential for pavement construction because it contains reusable aggregate and aged binder, reducing the demand for virgin asphalt materials. Fly ash and industrial by-products also contribute to sustainability by reducing cement consumption and improving long-term durability when used in suitable proportions. Therefore, the success of recycled materials depends on proper quality control rather than simple replacement of conventional materials. From a mechanical perspective, optimized recycled material blends can achieve acceptable strength, density, stability, and load-bearing behavior for many infrastructure applications. In some cases, their performance may approach or even match conventional materials, particularly when replacement ratios are carefully selected. However, durability remains an important concern and must be evaluated before field application. Properties such as water absorption, abrasion resistance, moisture sensitivity, freeze-thaw resistance, and long-term cracking behavior should be considered to ensure service-life reliability. This confirms that recycled materials should not be judged only on early strength results but should be assessed through a complete performance framework. The environmental benefits of recycled construction materials are highly significant. Their use reduces landfill disposal, decreases the extraction of virgin aggregates, lowers material transportation needs when local waste sources are used, and supports carbon reduction across the infrastructure life cycle. The study also supports the idea that recycled materials can reduce embodied carbon emissions by up to 35% when optimized processing and replacement strategies are applied. This demonstrates that recycled materials can contribute directly to climate-responsible construction and green infrastructure development. Economically, recycled materials can reduce construction costs by lowering the demand for virgin resources and minimizing waste disposal expenses. However, economic benefits are influenced by processing cost, transportation distance, availability, and quality control requirements. Therefore, the most suitable recycled material option should be selected through a multi-criteria decision framework that combines mechanical performance, durability, environmental impact, cost feasibility, and practical field applicability. Overall, this study confirms that recycled construction materials provide a promising pathway toward resilient, eco-efficient, and future-ready infrastructure systems. Their wider adoption requires technical standards, proper testing procedures, supportive policies, and confidence among engineers, contractors, and policymakers. Future research should focus on long-term field performance, large-scale application, advanced treatment methods, and standardized guidelines for recycled material use in different infrastructure conditions. By integrating recycled materials into mainstream construction practice, the infrastructure sector can move toward a more sustainable, resource-efficient, and environmentally responsible future.

## References

Ahmedzade, P., & Sengoz, B. (2009). Evaluation of steel slag coarse aggregate in hot mix asphalt concrete. *Journal of Hazardous Materials, 165*(1–3), 300–305.

Akhtar, A., & Sarmah, A. K. (2018). Construction and demolition waste generation and properties of recycled aggregate concrete: A global perspective. *Journal of Cleaner Production, 186*, 262–281.

Al-Qadi, I. L., Elseifi, M., & Carpenter, S. H. (2007). *Reclaimed asphalt pavement: A literature review*. Illinois Center for Transportation, University of Illinois at Urbana-Champaign.

Aravind, K., & Das, A. (2007). Pavement design with central plant hot-mix recycled asphalt mixes. *Construction and Building Materials, 21*(5), 928–936.

Behera, M., Bhattacharyya, S. K., Minocha, A. K., Deoliya, R., & Maiti, S. (2014). Recycled aggregate from C&D waste and its use in concrete: A breakthrough towards sustainability in construction sector. *Construction and Building Materials, 68*, 501–516.

Blengini, G. A. (2009). Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy. *Building and Environment, 44*(2), 319–330.

Bravo, M., de Brito, J., Pontes, J., & Evangelista, L. (2015). Mechanical performance of concrete made with aggregates from construction and demolition waste recycling plants. *Journal of Cleaner Production, 99*, 59–74.

Butler, L., West, J. S., & Tighe, S. L. (2013). Effect of recycled concrete coarse aggregate from multiple sources on the hardened properties of concrete with equivalent compressive strength.

*Construction and Building Materials, 47*, 1292–1301.

Copeland, A. (2011). *Reclaimed asphalt pavement in asphalt mixtures: State of the practice*. Federal Highway Administration.

Corinaldesi, V., & Moriconi, G. (2009). Influence of mineral additions on the performance of 100% recycled aggregate concrete. *Construction and Building Materials, 23*(8), 2869–2876.

de Brito, J., & Saikia, N. (2013). *Recycled aggregate in concrete: Use of industrial, construction and demolition waste*. Springer.

Etxeberria, M., Vázquez, E., Marí, A., & Barra, M. (2007). Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cement and Concrete Research, 37*(5), 735–742.

Evangelista, L., & de Brito, J. (2007). Mechanical behaviour of concrete made with fine recycled concrete aggregates. *Cement and Concrete Composites, 29*(5), 397–401.

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production, 114*, 11–32.

Hansen, T. C. (1992). *Recycling of demolished concrete and masonry*. CRC Press.

Huang, Y., Bird, R. N., & Heidrich, O. (2007). A review of the use of recycled solid waste materials in asphalt pavements. *Resources, Conservation and Recycling, 52*(1), 58–73.

International Organization for Standardization. (2006). *ISO 14040: Environmental management—Life cycle assessment—Principles and framework*. ISO.

International Organization for Standardization. (2006). *ISO 14044: Environmental management—Life cycle assessment—Requirements and guidelines*. ISO.

Katz, A. (2003). Properties of concrete made with recycled aggregate from partially hydrated old concrete. *Cement and Concrete Research, 33*(5), 703–711.

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

Kou, S. C., & Poon, C. S. (2012). Enhancing the durability properties of concrete prepared with coarse recycled aggregate. *Construction and Building Materials, 35*, 69–76.

Limbachiya, M. C., Leelawat, T., & Dhir, R. K. (2000). Use of recycled concrete aggregate in high-strength concrete. *Materials and Structures, 33*(9), 574–580.

Malhotra, V. M., & Mehta, P. K. (2005). *High-performance, high-volume fly ash concrete: Materials, mixture proportioning, properties, construction practice, and case histories*. Supplementary Cementing Materials for Sustainable Development Inc.

Marinković, S., Radonjanin, V., Malešev, M., & Ignjatović, I. (2010). Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Management, 30*(11), 2255–2264.

McDaniel, R., & Anderson, R. M. (2001). *Recommended use of reclaimed asphalt pavement in the Superpave mix design method: Technician's manual*. Transportation Research Board.

McNeil, K., & Kang, T. H. K. (2013). Recycled concrete aggregates: A review. *International Journal of Concrete Structures and Materials, 7*(1), 61–69.

Mehta, P. K., & Monteiro, P. J. M. (2014). *Concrete: Microstructure, properties, and materials* (4th ed.). McGraw-Hill Education.

Oikonomou, N. D. (2005). Recycled concrete aggregates. *Cement and Concrete Composites, 27*(2), 315–318.

Pacheco-Torgal, F., Tam, V. W. Y., Labrincha, J. A., Ding, Y., & de Brito, J. (Eds.). (2013). *Handbook of recycled concrete and demolition waste*. Woodhead Publishing.

Poon, C. S., Shui, Z. H., Lam, L., Fok, H., & Kou, S. C. (2004). Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. *Cement and Concrete Research, 34*(1), 31–36.

Khan, R., Khan, A., Muhammad, I., & Khan, F. (2025). A Comparative Evaluation of Peterson and Horvitz-Thompson Estimators for Population Size Estimation in Sparse Recapture Scenarios. *Journal of Asian Development Studies*, *14*(2), 1518-1527.

Shi, C., Fernández-Jiménez, A., & Palomo, A. (2011). New cements for the 21st century: The pursuit of an alternative to Portland cement. *Cement and Concrete Research, 41*(7), 750–763.

Siddique, R. (2004). Performance characteristics of high-volume Class F fly ash concrete. *Cement and Concrete Research, 34*(3), 487–493.

Siddique, R. (2008). *Waste materials and by-products in concrete*. Springer.

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

Tam, V. W. Y., Gao, X. F., & Tam, C. M. (2005). Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach. *Cement and Concrete Research, 35*(6), 1195–1203.

Thomas, M. D. A. (2007). *Optimizing the use of fly ash in concrete*. Portland Cement Association.

West, R. C., Willis, J. R., & Marasteanu, M. O. (2013). *Improved mix design, evaluation, and materials management practices for hot mix asphalt with high reclaimed asphalt pavement content*. Transportation Research Board.

Xiao, J., Li, W., Fan, Y., & Huang, X. (2012). An overview of study on recycled aggregate concrete in China. *Construction and Building Materials, 31*, 364–383.

Zaharieva, R., Buyle-Bodin, F., Skoczylas, F., & Wirquin, E. (2003). Assessment of the surface permeation properties of recycled aggregate concrete. *Cement and Concrete Composites, 25*(2), 223–232.

Zaumanis, M., Mallick, R. B., & Frank, R. (2014). 100% recycled hot mix asphalt: A review and analysis. *Resources, Conservation and Recycling, 92*, 230–245.