Volume 2, Issue 1, Jan – Jun 2026 Issue – Page no : 01-15

Integrated Journal of
Civil Engineering and Sustainable Technology

Performance Evaluation of Recycled Aggregate Concrete Incorporating Industrial By-Products for Sustainable Construction

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Abstract

The growing demand for natural construction materials and the increasing generation of construction and demolition waste have created significant environmental challenges for the construction industry. Recycled aggregate concrete (RAC) provides an alternative to conventional concrete by replacing a portion of natural aggregates with recycled concrete aggregates obtained from demolished structures. However, the presence of adhered mortar, higher water absorption and increased porosity in recycled aggregates may negatively influence the mechanical properties, workability and durability of concrete. The incorporation of industrial by-products, including fly ash, ground granulated blast furnace slag (GGBS) and silica fume, offers an opportunity to improve the performance of recycled aggregate concrete while reducing dependence on conventional cementitious materials. This paper presents a literature-based evaluation of the potential effects of recycled aggregates and industrial by-products on the fresh, mechanical and durability properties of concrete. An experimental evaluation framework is also proposed using different recycled aggregate replacement levels and supplementary cementitious material combinations. The assessment considers workability, compressive strength, splitting tensile strength, flexural strength, water absorption and durability characteristics. The discussion highlights the importance of aggregate quality, replacement proportions, water management and binder composition in producing sustainable concrete. The proposed framework provides a systematic basis for evaluating the technical suitability of industrial by-product-based recycled aggregate concrete for sustainable construction applications.

Index Terms— Recycled aggregate concrete, industrial by-products, fly ash, ground granulated blast furnace slag, silica fume, sustainable construction, compressive strength, concrete durability.

Received Date : 15.01.2026 **Publication Date : 25.01.2026**

I. INTRODUCTION

Concrete is one of the most widely used construction materials because of its strength, durability, availability and adaptability to different structural applications. The continuous expansion of infrastructure, residential buildings, transportation networks and industrial facilities has increased the demand for cement and natural aggregates. Conventional concrete production depends heavily on the extraction of natural resources, including river sand and crushed stone aggregates. Excessive extraction of these materials can contribute to environmental degradation, depletion of natural

resources and ecological disturbance.

At the same time, construction and demolition activities generate substantial quantities of concrete waste. The disposal of demolished concrete in landfills creates additional environmental and waste-management challenges. Recycling demolished concrete into usable aggregate provides an opportunity to reduce waste disposal and minimize the extraction of virgin aggregates. Recycled concrete aggregate (RCA) is generally obtained by crushing, screening and processing concrete recovered from demolished structures.

However, RCA differs from natural aggregate in several important physical characteristics. Recycled particles frequently contain adhered cement mortar from the original concrete. This adhered mortar can increase porosity and water absorption while reducing particle density and mechanical quality. These characteristics influence the fresh and hardened properties of concrete. Shi et al. [1] reported that the characteristics of adhered mortar are important factors affecting recycled aggregate performance. Similarly, investigations involving recycled aggregates have identified changes in workability, bleeding and hardened concrete properties [2], [3].

The use of industrial by-products as supplementary cementitious materials provides another opportunity to improve concrete sustainability. Fly ash, GGBS and silica fume are widely investigated as partial replacements for ordinary Portland cement. Their physical and chemical characteristics influence cement hydration, particle packing, pore structure and the interfacial transition zone between aggregate and cement paste.

Fly ash can contribute to later-age strength development through pozzolanic reactions. GGBS can contribute to binder hydration and long-term performance, while silica fume can improve particle packing and refine the cementitious matrix. The combined use of these materials with recycled aggregates may help address certain performance limitations associated with conventional recycled aggregate concrete.

Previous research has examined the mechanical and durability performance of recycled aggregate concrete incorporating fly ash, slag and silica fume [4]–[8]. Although substantial research has been conducted on individual recycled materials and supplementary cementitious materials, their combined performance requires careful evaluation under consistent mix-design and testing conditions.

This study therefore develops a systematic framework for evaluating recycled aggregate concrete incorporating industrial by-products for sustainable construction.

A. Research Objectives

The main objectives of this study are:

1. To examine the influence of recycled concrete aggregate replacement on the fresh and hardened properties of concrete.
2. To evaluate the potential contribution of fly ash, GGBS and silica fume to recycled aggregate concrete performance.
3. To establish a comparative experimental framework for different recycled aggregate and supplementary cementitious material combinations.
4. To identify appropriate mechanical and durability parameters for assessing sustainable concrete performance.
5. To discuss the technical considerations associated with using recycled aggregate concrete in construction applications.

B. Research Contributions

The study provides three main contributions:

- An integrated assessment framework considering aggregate properties, industrial by-products, mechanical performance and durability.
- A comparative concrete mix-design programme for evaluating individual and combined supplementary cementitious materials.
- A literature-supported framework for identifying suitable material combinations for sustainable concrete development.

II. LITERATURE REVIEW

A. Characteristics of Recycled Concrete Aggregate

Recycled concrete aggregate is generally produced by crushing concrete waste into coarse and fine aggregate fractions. The resulting particles may contain original natural aggregate surrounded by adhered hardened cement mortar.

Compared with natural aggregates, recycled aggregates can exhibit higher water absorption, lower density and greater variability in physical properties. These characteristics influence the amount of effective mixing water available during concrete production.

The presence of adhered mortar may also create additional interfacial transition zones within the hardened concrete. Multiple interfaces can influence stress transfer and contribute to variations in mechanical performance.

Shi et al. [1] reviewed techniques for improving recycled concrete aggregate performance and identified the importance of adhered mortar characteristics. Kou and Poon [2] investigated recycled concrete aggregates in self-compacting concrete and examined their effects on fresh and hardened properties.

B. Effect of Recycled Aggregate on Fresh Concrete

The workability of concrete is influenced by aggregate grading, particle shape, surface texture, moisture condition and water absorption.

Recycled aggregates may absorb a portion of the mixing water because of their porous adhered mortar. As a result, concrete mixtures containing high RCA replacement levels may experience reduced workability when moisture correction is not properly considered.

Poon et al. [3] investigated the influence of recycled aggregates on the slump and bleeding characteristics of fresh concrete. Their work highlights the importance of recycled aggregate moisture characteristics in controlling fresh concrete behaviour.

Appropriate aggregate moisture conditioning, optimized grading and suitable water-reducing admixtures can be considered during mix development.

C. Effect of Fly Ash on Recycled Aggregate Concrete

Fly ash is an industrial by-product generated during coal combustion. Its incorporation as a partial cement replacement has been investigated in various concrete applications.

Fly ash contains reactive silica and alumina components that may contribute to secondary hydration reactions in the presence of calcium hydroxide. These reactions can contribute to the formation of additional calcium silicate hydrate products.

In recycled aggregate concrete, fly ash may improve the cementitious matrix and contribute to later-age strength development. However, the performance depends on fly ash quality, fineness, replacement percentage, curing conditions and water-to-binder ratio.

Saravanakumar and Dhinakaran [4] evaluated the strength characteristics of high-volume fly ash-based recycled aggregate concrete, demonstrating the relevance of combined recycled aggregate and fly ash systems.

D. Effect of GGBS and Silica Fume

Ground granulated blast furnace slag is a supplementary cementitious material obtained through the processing of iron-making slag. Its latent hydraulic characteristics allow it to participate in cementitious reactions.

GGBS can contribute to later-age strength development and influence concrete permeability and durability. Its performance depends on material fineness, replacement level, curing conditions and overall binder composition.

Silica fume is a highly reactive fine material containing a high proportion of amorphous silica. Its fine particle size can improve the particle packing density of concrete. Its pozzolanic reaction can also contribute to matrix densification.

Kumar et al. [6] examined the strength and durability performance of recycled aggregate structural concrete incorporating silica fume, furnace slag and recycled fine material.

E. Combined Use of Industrial By-Products

The combined incorporation of fly ash, GGBS and silica fume offers the possibility of obtaining complementary effects within the cementitious matrix.

Fly ash can contribute to later-age pozzolanic reactions, GGBS can contribute to hydraulic and pozzolanic binder development, and silica fume can refine particle packing and the interfacial transition zone.

Experimental studies have examined combinations of RCA and multiple supplementary cementitious materials in self-compacting concrete [5]. Other investigations have studied recycled aggregates incorporating fly ash, metakaolin and silica fume [7].

The findings indicate that the combined material system must be optimized rather than assuming that increasing the replacement percentage will always improve performance.

F. Research Gap

The literature establishes the potential benefits and limitations of recycled aggregate concrete and supplementary cementitious materials. However, comparisons across different studies are often affected by variations in aggregate source, original concrete quality, water-to-binder ratio, curing conditions and test procedures.

A systematic comparative investigation is therefore required to evaluate:

- The influence of different RCA replacement levels.
- The effects of individual and combined industrial by-products.
- The relationship between workability and hardened concrete strength.
- The influence of supplementary cementitious materials on water absorption and durability.

- The balance between material utilization, engineering performance and sustainable construction requirements.

The proposed evaluation framework addresses these considerations through a controlled concrete mix programme.

III. MATERIALS AND METHODOLOGY

The proposed experimental programme is designed to investigate the combined influence of recycled concrete aggregate and industrial by-products on concrete performance. The methodology considers material characterization, mix preparation, fresh concrete testing, hardened concrete testing and comparative performance evaluation.

A. Materials

The following materials are considered for the proposed concrete mixtures.

1) Ordinary Portland Cement: Ordinary Portland cement (OPC) is used as the primary binding material. Its physical properties, specific gravity, fineness and setting characteristics should be determined before preparing the concrete mixtures.

2) Natural Coarse Aggregate: Natural crushed stone aggregate is used as the reference coarse aggregate. The particle size distribution, specific gravity, water absorption and aggregate crushing characteristics should be evaluated.

3) Recycled Concrete Aggregate: RCA is obtained from processed concrete demolition waste. The collected material should be crushed, screened and separated into suitable size fractions. Loose impurities, wood, plastic, soil and other unwanted materials should be removed before use.

4) Fly Ash: Fly ash is considered as a partial replacement for cement. Its fineness, chemical composition and physical characteristics should be recorded.

5) Ground Granulated Blast Furnace Slag: GGBS is incorporated as a supplementary cementitious material to investigate its influence on binder development, strength and durability.

6) Silica Fume: Silica fume is considered as a highly reactive supplementary cementitious material for improving particle packing and the characteristics of the cementitious matrix.

7) Fine Aggregate and Water: Clean natural fine aggregate and potable-quality mixing water should be used. The aggregate moisture condition must be measured before preparing each mixture.

B. Characterization of Recycled Aggregate

The quality of RCA is an important factor influencing concrete performance. Recycled aggregates should be evaluated before incorporation into the concrete mixture.

The following properties are recommended:

- Particle size distribution and grading.
- Specific gravity and bulk density.
- Water absorption.
- Aggregate impact and crushing resistance.
- Percentage of adhered mortar, where measurable.

- Visual contamination and particle shape.

The water absorption of RCA must be considered when determining the effective mixing water. Pre-soaking or controlled moisture conditioning can be adopted to improve consistency between concrete batches.

C. Proposed Concrete Mix Design

A control mixture and seven modified mixtures are proposed to investigate the effects of recycled aggregates and industrial by-products.

The coarse aggregate replacement percentage is calculated by volume, whereas cement replacement percentages are calculated by mass of total binder.

TABLE I. PROPOSED CONCRETE MIXTURE COMBINATIONS

Mix ID	RCA replacement	Fly ash	GGBS	Silica fume
M0	0%	0%	0%	0%
M1	50%	0%	0%	0%
M2	100%	0%	0%	0%
M3	50%	15%	0%	0%
M4	50%	0%	20%	0%
M5	50%	0%	0%	7.50%
M6	50%	10%	10%	0%
M7	50%	10%	10%	5%

Note: These are proposed trial proportions, not experimentally validated optimum values. All percentages of supplementary materials are cement replacement percentages. Final proportions should be established through preliminary mix trials and applicable mix-design procedures.

The water-to-binder ratio, aggregate grading and total binder content should be maintained consistently across the comparison wherever practicable. The quantity of superplasticizer may be adjusted to achieve the specified workability, with each adjustment documented.

D. Concrete Mixing and Specimen Preparation

The concrete constituents should be prepared and measured according to the approved mix proportions. RCA moisture conditioning should be completed before mixing to minimize uncontrolled water absorption.

The mixing procedure consists of the following stages:

1. Measure cement, natural aggregates, recycled aggregates and supplementary cementitious materials.
2. Dry-mix the cementitious materials and aggregates until uniform distribution is achieved.
3. Add the calculated mixing water gradually.
4. Incorporate the chemical admixture, where required.
5. Continue mixing until a uniform concrete mixture is obtained.

6. Perform fresh concrete tests.
7. Cast concrete specimens into properly prepared moulds.
8. Compact the specimens using an appropriate procedure.
9. Demould after the specified initial curing period and transfer to controlled curing conditions.
10. Test the specimens at the specified ages.

At least three specimens should be tested for each mixture and test age, with additional specimens provided where required by the selected testing standard.

E. Fresh Concrete Testing

Fresh concrete properties determine the suitability of the mixture for transportation, placement, compaction and construction operations.

1) Slump Test: The slump test is used to examine the consistency and workability of fresh concrete. A reduction in slump may occur when recycled aggregates absorb a portion of the mixing water.

2) Fresh Density: Fresh density is measured to examine changes associated with aggregate replacement and binder composition. Differences in aggregate density may influence the density of the resulting concrete.

3) Workability Assessment: The results should be evaluated alongside water-to-binder ratio and admixture dosage. This is important because improvements in slump achieved through additional water should not be interpreted as an improvement in material performance.

F. Mechanical Property Evaluation

Mechanical performance is assessed through compressive strength, splitting tensile strength and flexural strength tests.

1) Compressive Strength: Compressive strength is determined using concrete cube or cylindrical specimens following a consistent applicable testing procedure. The maximum load sustained by each specimen is recorded and used to determine its compressive strength. Results should be compared across mixtures and curing ages.

2) Splitting Tensile Strength: Splitting tensile strength is evaluated using cylindrical concrete specimens subjected to diametral compression. The test provides an indication of the concrete's resistance to tensile cracking.

3) Flexural Strength: Flexural performance is evaluated using beam specimens under third-point loading. This test helps assess the ability of concrete to resist bending-induced tensile stresses.

These mechanical parameters provide an understanding of the influence of recycled aggregates and industrial by-products on the load-resisting characteristics of concrete.

G. Durability Evaluation

Durability testing is essential because recycled aggregates may contain porous adhered mortar and additional interfaces within the concrete matrix.

1) Water Absorption: Water absorption is determined by comparing the dry mass and saturated mass of concrete specimens. Higher water absorption may indicate greater accessible pore volume and potential moisture transport.

2) Sorptivity: Sorptivity measures the rate at which water enters concrete through capillary suction. It provides information about the transport characteristics of the cementitious matrix.

3) Chloride Ion Penetration: Chloride penetration resistance can be examined using an appropriate standardized test method. This parameter is particularly relevant to reinforced concrete structures exposed to chloride-containing environments.

4) Drying Shrinkage: Drying shrinkage measurements are recommended to evaluate volume changes associated with moisture loss.

5) Sulphate Resistance: Where relevant to the intended construction environment, sulphate exposure testing can be used to examine the resistance of concrete specimens to aggressive chemical conditions.

H. Data Analysis

The experimental measurements should be evaluated using mean values, standard deviation and coefficient of variation. These statistical indicators help determine the consistency and repeatability of test results.

For each mix and test condition, the average of repeated specimen measurements should be reported along with the variation among specimens.

The relative strength retention of each recycled aggregate mixture should be assessed by comparing its compressive strength with that of the control mixture at the same curing age.

Statistical analysis, including analysis of variance (ANOVA), may be used to determine whether observed differences between mixtures are statistically significant. A significance level of 0.05 may be adopted, subject to the experimental design.

IV. LITERATURE-BASED PERFORMANCE EVALUATION

The performance of recycled aggregate concrete incorporating industrial by-products is influenced by the combined effects of aggregate properties, binder characteristics and curing conditions.

A. Effect on Workability

RCA has a relatively porous structure because of adhered cement mortar. Its water absorption characteristics can influence the effective water available during mixing. In addition, particle angularity and surface texture may increase the internal friction within the fresh concrete mixture.

Studies on recycled aggregate self-compacting concrete have reported changes in fresh concrete properties with variations in aggregate replacement [2]. Poon et al. [3] also examined the effects of recycled aggregates on slump and bleeding.

The use of fly ash and suitable chemical admixtures may help manage fresh concrete behaviour. However, the workability response should be evaluated experimentally rather than assumed to improve for every industrial by-product combination.

B. Effect on Compressive Strength

Compressive strength is one of the primary parameters used to evaluate concrete performance.

The incorporation of RCA may influence compressive strength because of differences in aggregate quality, adhered mortar and interfacial bonding. A higher replacement percentage does not necessarily produce equivalent strength to conventional concrete.

The incorporation of fly ash, GGBS and silica fume may modify the cementitious matrix and improve the interface between aggregate and paste when suitable proportions and curing conditions are used.

Guo et al. [5] investigated sustainable self-compacting concrete containing RCA, fly ash, slag and silica fume. Their research examined how combinations of supplementary cementitious materials could compensate for some adverse effects associated with RCA incorporation.

Saravanakumar and Dhinakaran [4] studied high-volume fly ash-based recycled aggregate concrete, demonstrating the relevance of investigating binder replacement and aggregate replacement together.

C. Effect on Tensile and Flexural Strength

Tensile and flexural characteristics are important for evaluating cracking resistance and structural behaviour.

The recycled aggregate interface may influence crack initiation and propagation. The quality of adhered mortar, aggregate strength and paste–aggregate bonding can contribute to differences in tensile and flexural performance.

Silica fume may contribute to matrix densification, while GGBS and fly ash can influence binder development. Nevertheless, the effect of these materials must be evaluated using direct tensile and flexural tests.

The combined effects of silica fume and furnace slag in recycled aggregate structural concrete have been investigated by Kumar et al. [6].

D. Effect on Water Absorption and Durability

Water absorption and permeability are important indicators of concrete durability.

RCA may introduce additional porous regions through adhered mortar and old interfacial transition zones. These regions can provide pathways for water movement and influence the transport of aggressive substances.

The use of suitable supplementary cementitious materials may refine pore structure through particle packing and cementitious reactions. However, the actual durability response depends on material quality, replacement proportions and curing.

Alamri et al. [7] investigated recycled aggregate concrete incorporating fly ash, metakaolin and silica fume, considering both mechanical and durability characteristics.

E. Effect on Shrinkage and Creep

Shrinkage and creep are important considerations in reinforced concrete structures and long-term serviceability.

Recycled aggregates can affect deformation behaviour due to differences in moisture absorption, stiffness and adhered mortar content. The use of multiple supplementary cementitious materials may also alter the time-dependent behaviour of concrete.

Qin et al. [8] investigated shrinkage and creep in sustainable self-compacting concrete containing recycled aggregates, fly ash, slag and silica fume. Their findings showed that the influence of these materials depended on the combination and replacement levels used.

F. Comparative Performance Summary

TABLE II. QUALITATIVE PERFORMANCE TRENDS REPORTED IN THE LITERATURE

Material combination	Workability	Strength development	Durability
Natural aggregate concrete	Reference	Reference	Reference
RCA concrete	May decrease	May decrease	Depends on RCA quality
RCA + fly ash	Mix-dependent	May improve at later ages	Potential improvement
RCA + GGBS	Mix-dependent	Potential later-age improvement	Potential improvement
RCA + silica fume	May require admixture adjustment	Potential matrix improvement	Potential pore refinement
RCA + combined SCMs	Depends on proportions	Potential complementary effects	Requires long-term validation

Note: This table is a qualitative synthesis of published research, not a set of measurements from the proposed experimental programme.

G. Literature-Based Factor–Property Comparison

TABLE III. QUALITATIVE INFLUENCE OF MATERIALS ON CONCRETE PERFORMANCE

Performance parameter	RCA alone	Fly ash	GGBS	Silica fume	Combined SCMs
Workability	Variable	Variable	Variable	Variable	Mix-dependent
Early-age strength	Variable	Often slower	Mix-dependent	Potential improvement	Mix-dependent
Later-age strength	Variable	Potential improvement	Potential improvement	Potential improvement	Potential improvement
Water absorption	Potential increase	Potential reduction	Potential reduction	Potential reduction	Potential reduction
Shrinkage	Potential increase	Mix-dependent	Mix-dependent	Mix-dependent	Mix-dependent
Durability	RCA-dependent	Potential improvement	Potential improvement	Potential improvement	Potential improvement

Note: The table summarizes qualitative trends and does not represent measured numerical performance or a universal ranking of materials.

V. RESULTS AND DISCUSSION

This section separates findings reported in previous experimental studies from the results that must be generated through the proposed experimental programme. Since no laboratory measurements are available for the present work, the following discussion represents a literature-based performance assessment rather than newly obtained experimental results.

A. Published Quantitative Evidence

Qin et al. [8] investigated recycled aggregate self-compacting concrete incorporating fly ash, slag and silica fume. Their experimental results provide a useful example of how aggregate replacement and supplementary cementitious materials can influence long-term deformation.

TABLE IV. SELECTED QUANTITATIVE FINDINGS FROM A PUBLISHED STUDY

Evaluation condition	Reported result
100% RCA: increase in shrinkage relative to control	Up to 37.2%
100% RCA: increase in creep relative to control	Up to 33.5%
Fly ash and slag combination: reduction in shrinkage	27.6%
Combined fly ash, slag and silica fume: reduction in specific creep	27.9%

Source: Qin et al. [8]. These values belong to the cited study's particular self-compacting concrete mixtures and testing conditions; they are not results from the proposed study.

Values reported by Qin et al. (2022), not measurements from the proposed study.

-35%-15%5%25%45%RCA shrinkageRCA creepFA + GGBS shrinkageFA + GGBS + SF creep

The published evidence illustrates two important considerations. First, high recycled aggregate replacement can increase long-term deformation. Second, appropriately selected combinations of supplementary cementitious materials can reduce certain adverse effects. However, the suitability of a particular combination must be established through controlled testing.

B. Interpretation of Mechanical Performance

The mechanical performance of recycled aggregate concrete is influenced by aggregate quality, binder composition, curing conditions and interfacial bonding.

A reduction in compressive strength may occur when recycled aggregate contains significant quantities of porous adhered mortar. The additional interfacial transition zones may also influence stress distribution and failure behaviour.

The use of fly ash, GGBS and silica fume provides different mechanisms for improving the cementitious matrix. Fly ash and GGBS can contribute to later-age strength development, while silica fume may improve matrix packing and interface characteristics.

The important consideration is the balance between RCA replacement and binder quality. A mixture containing a higher quantity of industrial by-products is not automatically superior. The material proportions should be selected according to measured strength, workability and durability requirements.

C. Interpretation of Durability Performance

Durability should be assessed using multiple indicators rather than a single water absorption measurement.

Concrete with lower water absorption may exhibit improved resistance to water transport. However, water absorption alone cannot fully establish resistance to chloride penetration, sulphate attack, carbonation or freeze–thaw exposure.

For this reason, a comprehensive evaluation should include relevant durability tests based on the intended structural application and environmental exposure.

D. Practical Implications for Sustainable Construction

The proposed concrete system has potential applications where recycled aggregate quality and structural performance can be adequately controlled.

Possible applications include:

- Non-critical concrete elements and secondary construction components.
- Pavement and infrastructure applications after appropriate performance validation.
- Precast concrete products produced under controlled manufacturing conditions.
- Sustainable building components using verified recycled material sources.
- Selected structural concrete applications when the required design properties are demonstrated.

The use of RCA should not be treated as a direct replacement for natural aggregate without material characterization. Engineering approval should be based on the properties of the final concrete rather than the environmental benefit of recycling alone.

VI. SUSTAINABILITY ASSESSMENT

Sustainability evaluation requires consideration of material consumption, waste utilization, energy demand and environmental impact.

A. Natural Aggregate Conservation

The replacement of natural coarse aggregate with RCA can reduce the demand for newly extracted natural materials. The proportion of recycled aggregate used in each concrete mixture should be documented to evaluate the extent of natural resource conservation.

A higher RCA replacement percentage indicates greater utilization of recycled aggregate, although the resulting concrete must still meet the required engineering performance.

B. Cement Replacement and Industrial Waste Utilization

The incorporation of industrial by-products can reduce the proportion of ordinary Portland cement used in concrete.

The total quantity of fly ash, GGBS and silica fume incorporated into each mixture should be recorded. This allows the contribution of industrial by-products to the overall binder composition to be evaluated.

C. Environmental Impact Evaluation

A comparative environmental assessment can be conducted using a life-cycle assessment approach. The system boundary should include raw material acquisition, transportation, processing, concrete production and relevant construction stages.

The assessment should include the environmental burdens associated with RCA collection, crushing, screening, transportation and processing. Industrial by-products should also be assigned appropriate environmental accounting assumptions.

A recycled aggregate mixture cannot automatically be considered lower-carbon without evaluating these processes and the complete system boundary.

D. Sustainable Material Selection

The selection of an appropriate concrete mixture should consider engineering performance and environmental contribution together.

TABLE V. PROPOSED SUSTAINABILITY EVALUATION PARAMETERS

Sustainability factor	Evaluation parameter
Natural resource conservation	RCA replacement percentage
Industrial waste utilization	Total SCM replacement percentage
Cement consumption	OPC mass per cubic metre
Concrete performance	Strength retention
Durability	Water absorption and permeability
Construction suitability	Workability and density
Environmental performance	Life-cycle impact assessment

The combined evaluation provides a more complete understanding of the suitability of recycled aggregate concrete for sustainable construction.

VII. LIMITATIONS AND FUTURE RESEARCH

Although recycled aggregate concrete incorporating industrial by-products offers potential environmental and technical benefits, certain limitations must be addressed.

First, the quality of RCA varies according to the source of demolished concrete, processing techniques and adhered mortar content. This variability can produce differences in concrete properties even when identical replacement percentages are used.

Second, the interaction between different supplementary cementitious materials is complex. Fly ash, GGBS and silica fume have different physical and chemical characteristics, and their combined influence depends on replacement levels and curing conditions.

Third, long-term durability requires further investigation under different environmental exposure conditions. Important areas include chloride penetration, carbonation, sulphate resistance, drying shrinkage and creep.

Fourth, the environmental benefits of recycled aggregate concrete should be quantified through life-cycle assessment rather than inferred only from recycled material content.

Future studies should investigate optimized multi-component binder systems, advanced RCA surface treatment, microstructural characterization and the use of machine-learning techniques for predicting concrete performance.

VIII. CONCLUSION

This paper presented a literature-based performance evaluation framework for recycled aggregate concrete incorporating industrial by-products for sustainable construction. The study considered the combined influence of recycled concrete aggregate, fly ash, ground granulated blast furnace slag and silica fume on the fresh, mechanical and durability characteristics of concrete.

The literature indicates that recycled aggregates offer opportunities to conserve natural resources and utilize construction and demolition waste. However, adhered mortar, higher water absorption and variations in aggregate quality may influence workability, strength and long-term durability.

The incorporation of industrial by-products provides a potential approach for improving the cementitious matrix and reducing dependence on ordinary Portland cement. Fly ash, GGBS and silica fume offer complementary material characteristics, although their performance depends on replacement proportions, material quality and curing conditions.

The proposed experimental programme includes eight concrete mixtures with different RCA and supplementary cementitious material combinations. Workability, compressive strength, splitting tensile strength, flexural strength, water absorption and durability are identified as the primary evaluation parameters.

Published studies also demonstrate that RCA replacement can influence shrinkage and creep, while selected supplementary cementitious material combinations may mitigate certain adverse effects. These findings support the need for a comprehensive evaluation of mechanical performance, durability and sustainability.

Overall, recycled aggregate concrete incorporating industrial by-products represents a promising material system for sustainable construction. However, its practical implementation should be supported by systematic experimental validation, appropriate mix optimization, durability assessment and environmental evaluation.

Future experimental validation is necessary before identifying an optimum mixture or recommending the proposed material combinations for structural applications.

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