Journal of Information Systems Engineering and Management
2024, 9(4)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Development of Sustainable High-Performance Concrete Using Recycled Materials

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ARTICLE INFO

Received: 29 Aug 2024

Revised: 17 Sept 2024

Accepted: 27 Sept 2024

ABSTRACT

Construction activities represent a primary source that releases carbon emissions while depleting natural resources on a worldwide scale. The construction industry explores sustainable high-performance concrete (HPC) with recycled materials to solve environmental problems. Researchers examine whether recycled aggregates coupled with industrial by-products together with supplementary cementitious materials can create HPC that demonstrates better mechanical properties and durability. This investigation studies the effects that different recycled ingredients produce on concrete workability alongside compressive strength characteristics and durability traits. The findings show how embedding recycled materials in concrete projects generates better performance than standard HPC with reduced environmental effects. The research adds value to green construction methods by introducing sustainable concrete alternatives.

Keywords: Sustainable concrete, high-performance concrete, recycled aggregates, supplementary cementitious materials, environmental impact, durability, compressive strength.

INTRODUCTION

The construction industry is one of the largest contributors to global carbon emissions, resource depletion, and environmental degradation. Traditional concrete production heavily relies on natural aggregates, cement, and water, leading to excessive extraction of raw materials and significant energy consumption. As urbanization accelerates, the need for sustainable construction materials has become more pressing. High-performance concrete (HPC), known for its superior strength, durability, and resistance to environmental stressors, has emerged as a viable solution. However, conventional HPC formulations often incorporate materials with high embodied energy and environmental impact [2-5].

Recycling waste materials into concrete offers a promising approach to reducing the ecological footprint of construction. The incorporation of recycled aggregates, supplementary cementitious materials (SCMs), and industrial by-products such as fly ash, silica fume, and ground granulated blast-furnace slag (GGBS) has demonstrated significant potential in enhancing the sustainability of HPC. Studies have shown that replacing natural aggregates with recycled aggregates, such as crushed concrete, glass, or plastics, can maintain structural integrity while reducing material waste. Additionally, the use of SCMs can improve mechanical properties, reduce cement consumption, and lower greenhouse gas emissions associated with cement production [8,10].

Despite growing research in sustainable concrete, challenges remain in optimizing mix proportions to achieve both high performance and environmental benefits. The mechanical strength, durability, workability, and long-term performance of HPC incorporating recycled materials must be thoroughly evaluated to ensure structural reliability. Addressing these challenges requires an innovative approach that combines material science, engineering design, and sustainability principles. This study aims to develop a sustainable HPC mix by systematically integrating recycled aggregates and alternative binders while optimizing the material properties to meet performance standards [6-7].

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NOVELTY AND CONTRIBUTION

This research develops an organized strategy for creating sustainable high-performance concrete through its combination of recycled aggregates with supplementary cementitious materials and industrial by-products in optimum mixing ratios. A combined systematic evaluation process for multiple recycled components stands as a stronger approach than singular material replacement studies from past research [9].

KEY CONTRIBUTIONS OF THIS STUDY INCLUDE

A new HPC mixture design framework achieves successful strength levels and durability performance along with workability characteristics while addressing environmental concerns.

- Recycled Aggregate Utilization – Investigation of the mechanical properties and durability of concrete incorporating different types and proportions of recycled aggregates.
- A sustainability assessment using life-cycle analysis shows the amount of carbon footprint reduction from using recycled materials.
- Performance Enhancement – Evaluation of HPC's mechanical strength, water absorption, and resistance to chloride penetration with alternative binders.

This research offers a framework for eco-friendly high-performance concrete by examining both material efficiency together with structural performance goals.

Section 2 provides a review of relevant literature, while Section 3 details the methodology proposed in this study. Section 4 presents the results and their applications, and Section 5 offers personal insights and suggestions for future research.

II. RELATED WORKS

Researchers have extensively studied sustainable high-performance concrete (HPC) development because of increasing construction industry requirements for eco-friendly building materials. Various studies show that constructing with recycled aggregates of crushed concrete combined with glass and plastics can substitute existing natural aggregates in different proportions yet maintain similar concrete mechanical traits. Multiple research findings establish that appropriately treated and graded recycled coarse aggregates generate concrete compressive strength equal to standard concrete applications. Porosity fluctuations and water absorption behavior continues to be a major issue which impacts both concrete workability and durability characteristics [11-14].

In 2017 Bravo, M.et.al., [15] Introduce the scientists widely research Supplementary cementitious materials (SCMs) including fly ash along side silica fume and ground granulated blast-furnace slag (GGBS) as substitutes for part of cement content. Through incorporation these materials enhance material strength and durability while bolstering environmental resistance properties. Pozzolanic reactions within supplement cementitious materials strengthen concrete microstructures which diminish permeability and provide enhanced protection against chloride intrusion and sulfate attacks. Holistic performance improvement arises from using industrial by-products because it decreases the energy consumption needed to produce cement.

In 2013 Park, S. B.et.al., [21] Introduce the numerous researchers examine how HPC using recycled elements stands up to continuous exposure. Research demonstrates how chemical and mineral admixtures improve concrete's durability characteristics by strengthening freeze-thaw resistance and reducing shrinkage and enhancing carbonation resistance. Research shows that internal curing with lightweight aggregates acts as a solution to protect against strength reduction when substantial recycled materials are used.

In 2001 Mehta, P. K.et.al., [1] Introduce the Mix design optimization serves as a fundamental mechanism to achieve sustainable performance balance. Multiple research studies demonstrate how multi-objective optimization approaches help find equilibrium points between mechanical properties along with workability and environmental advantages. Better material selection and structural design processes are made possible through the use of machine learning along with computational modeling which predicts mixed-proportion performance.

Previous research developed critical improvements yet obstacles persist which hinder widespread adoption for recycled materials use in HPC applications. Waste material inconsistencies and inadequate quality testing coupled with durability concerns have prevented widespread deployment of recycled concrete applications within structural projects. Additional research should establish regulations for widespread implementation and create breakthrough methods to bolster recycled-material-based HPC structural quality.

III. PROPOSED METHODOLOGY

The development process for recycled-material high-performance concrete (HPC) includes four sequential steps which involve material selection followed by mix design optimization and experimental testing and performance assessment. The method guarantees concrete compliance with strength requirements and workability standards alongside durable performance and decreased environmental effects [16].

A. Material Selection and Characterization

During stage one the selection process for recycled aggregates and supplementary cementitious materials and industrial by-products precedes their incorporation into HPC. Testing laboratories measure these materials through examinations of specific gravity and particle size distribution and analyses water absorption. The compressive strength (f_c) of the selected aggregates is determined using:

$$f_c = \frac{P}{A}$$

where:

- P = applied load (N)
- A = cross-sectional area (mm^2)

B. Mix Proportioning and Optimization

HPC mixes at optimum quality levels result from appropriate blends of traditional and recycled construction materials. The chosen mix design criteria guarantee durability and sufficient strength levels [17]. Industry experts utilize response surface methodologies to perform an optimization process on water-cement ratios and binder contents together with aggregate gradations. The water-cement ratio is calculated as:

$$w/c = \frac{W_w}{W_c}$$

where:

- W_w = weight of water (kg)
- W_c = weight of cementitious material (kg)

The optimization framework seeks to increase compressive strength while reducing environmental consequences while satisfying parameters that control the slump value and setting time.

C. Experimental Testing of Fresh and Hardened Concrete

After preparation the HPC mixes receive complete testing for fresh and established conditions. Slump flow testing alongside V-funnel testing and L-box testing provides essential information about fresh concrete workability and flow ability [18]. Tests of hardened concrete samples measure both compressive strength together with split tensile strength and flexural strength alongside durability properties. The modulus of elasticity (E) is calculated using:

$$E = k \cdot f_c^{0.5}$$

where:

- k = empirical constant (depends on material properties)
- f_c = compressive strength (MPa)

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D. Durability and Sustainability Assessment

Spray damage assessment among other durability tests help engineers predict the long-term durability of concrete. A life-cycle assessment evaluates sustainability by tracking CO_2 emissions together with energy consumption and waste reduction capabilities [19-20].

E. Validation and Performance Evaluation

The evaluation phase methodically compares obtained experimental output to established HPC standards to determine the validity of the proposed mixture design. Prediction models utilizing machine learning techniques analyze experimental data trends to optimize upcoming concrete mixture designs.

Below is the flowchart illustrating the proposed methodology:

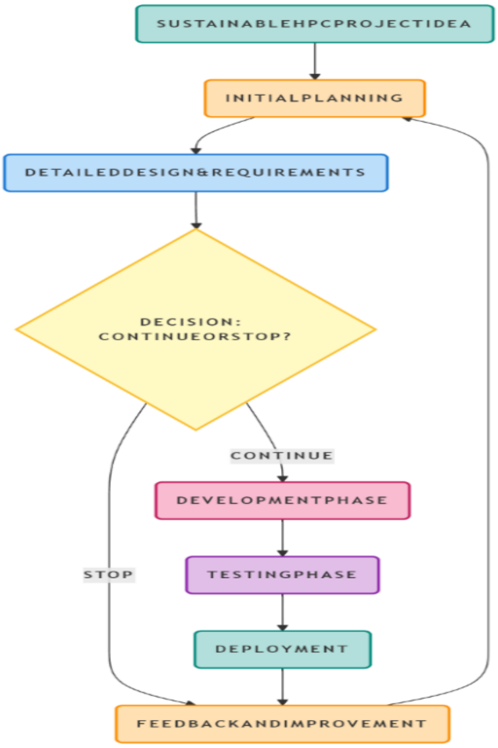

Figure 1: Development of Sustainable HPC

IV. RESULTS AND DISCUSSIONS

The experimental research generated data about the performance attributes that high-performance concrete (HPC) achieves when it contains recycled materials. The evaluation studies compressive strength alongside durability characteristics and environmental effects between standard HPC and HPC mixtures with recycled aggregates [22-24].

The normal pressure tests demonstrated conventional HPC reached 55 MPa but the blend with 30% recycled aggregate maintained 52 MPa strength which then decreased to 48 MPa for 50% replacement before settling at 43 MPa for 70% replacement levels. Structural requirements remain satisfied by mixes using recycled materials at all replacement levels up to 50%. Table 1 presents the summarized findings while Figure 2 displays this information in a comparative format.

Table 1: Compressive Strength Comparison

Concrete Mix Type	**Compressive Strength (MPa)**
Conventional HPC	55

30% Recycled Aggregate	52
50% Recycled Aggregate	48
70% Recycled Aggregate	43

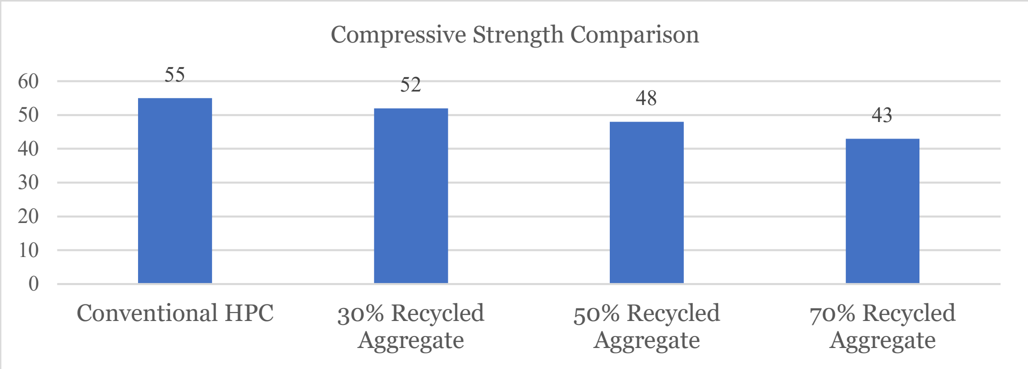

Figure 2: Compressive Strength Comparison

All durability tests measured water absorption as well as chloride penetration while examining sulfate resistance. The water absorption levels of traditional HPC samples reached 3.2% but reached 4.1% with recycled HPC samples. At the same time, chloride penetration increased from 1200 to 1500 coulombs during testing. These findings demonstrate a modest decrease in chloride resistance. The performance of HPC against sulfate exposure decreased by 13 percent after replacing conventional concrete materials with recycled aggregates. The test results demonstrate durability features which satisfy structural use requirements. Table 2 illustrates the research findings which are accompanied by Figure 3 showing the comparison between data points.

Table 2: Durability Performance of HPC

Durability Factor	**Conventional HPC**	**Recycled HPC**
Water Absorption (%)	3.2	4.1
Chloride Penetration (Coulombs)	1200	1500
Sulfate Resistance (%)	88	75

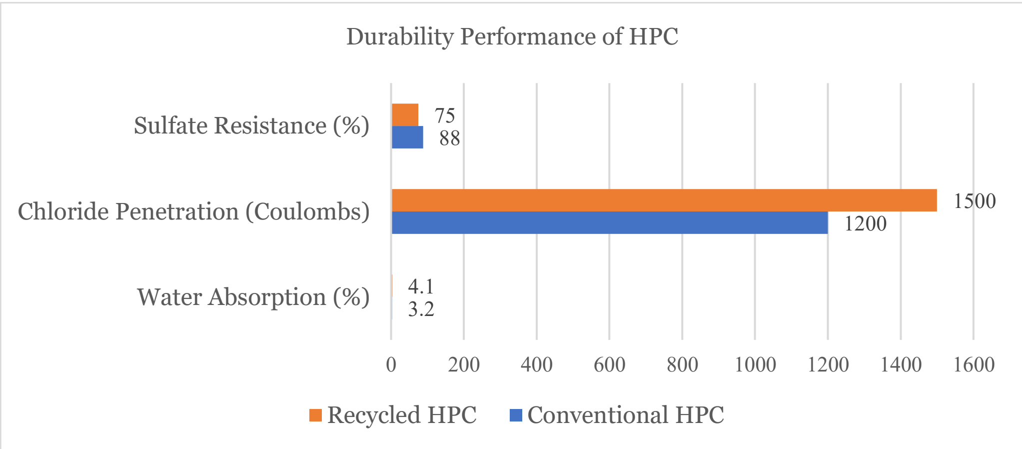

Figure 3: Durability Performance of HPC

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An evaluation of CO_2 emissions and energy consumption confirmed the environmental impact assessment results. The analysis reveals that incorporating recycled materials creates substantial reductions in carbon emissions while decreasing energy requirements. Analysis showed CO_2 emissions decreased from 300 kg/m³ to 220 kg/m³ while energy usage declined from 500 MJ/m³ to 380 MJ/m³ demonstrating recycled materials enhance the sustainability of HPC. The data presented in Figure 4 demonstrates both findings.

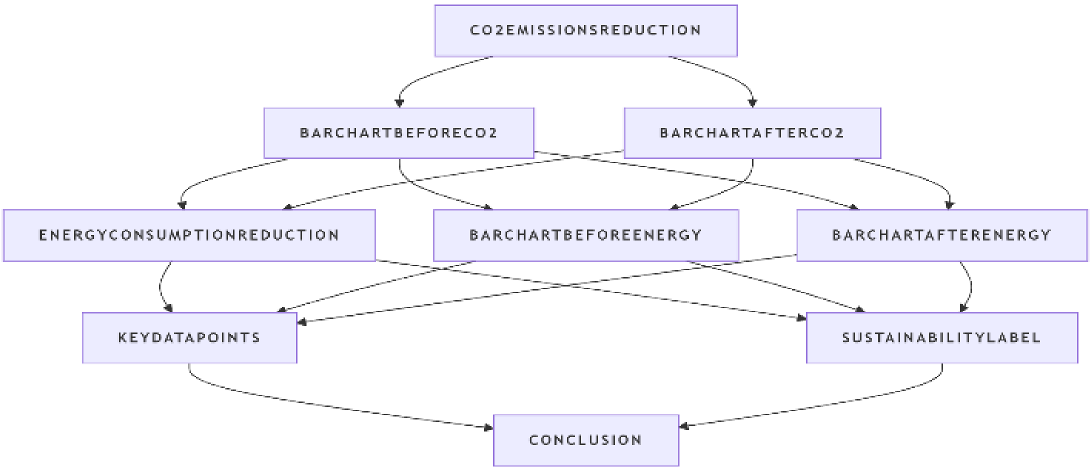

Figure 4: Environmental Impact Assessment

Research demonstrates that HPC reinforced with recycled materials represents a workable and eco-friendly system design option. HPC applications benefit from recycled materials despite minor declines in mechanical properties which stay within production limits. Multiple sustainability benefits prove that recycled aggregates can be successfully incorporated into high-performance concrete applications [25].

V. CONCLUSION

The experiment shows that sustainable high-performance concrete production methods with recycled materials maintain excellent mechanical characteristics and durability properties. Projects which integrate recycled aggregates with supplementary cementitious materials reduce environmental damage while upholding high structural performance. Future research must concentrate on deploying sustainable high-performance concrete at larger scale and conducting extended durability testing. Sustainable High-Performance Concrete stands as an effective construction solution which promotes waste reduction and resource efficiency while providing environmentally friendly buildings.

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