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ENVIRONMENTAL AND ECONOMIC IMPLICATIONS OF REPLACING NATURAL GRAVEL WITH BOTTOM ASH GRANULATE FRACTIONS (BGF) IN UHPC

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ABSTRACT

The increasing scarcity of high-quality natural aggregates and the environmental concerns associated with their extraction have prompted the search for sustainable alternatives in the production of ultra-high-performance concrete (UHPC). This study investigates the environmental and economic implications of partially or fully replacing natural gravel with bottom ash granulate fractions (BGF) as a coarse aggregate in UHPC. A comprehensive experimental program was conducted to evaluate the fresh and hardened properties of UHPC mixes incorporating varying proportions of BGF, including workability, compressive strength, flexural behavior, and durability indicators. Life cycle assessment (LCA) and cost–benefit analysis (CBA) were employed to quantify the environmental footprint and economic feasibility of BGF substitution.

The results reveal that BGF-modified UHPC exhibits competitive mechanical performance, with compressive strength reductions within acceptable ranges (<10%) when up to 50% replacement is applied. Durability indicators, such as chloride penetration resistance and shrinkage behavior, remained comparable to conventional UHPC, suggesting that BGF integration does not compromise long-term performance. The LCA results indicate a significant reduction in carbon dioxide emissions and primary energy demand, primarily due to the avoided extraction and processing of natural gravel. Economically, BGF utilization demonstrated cost savings of 12–18% in material procurement, depending on the substitution level, owing to the lower acquisition and processing costs of bottom ash.

The findings highlight the dual benefit of BGF integration: reducing the reliance on non-renewable natural aggregates and valorizing an industrial by-product that otherwise poses disposal challenges. Thus, incorporating BGF in UHPC not only aligns with circular economy principles but also offers a viable pathway for sustainable and cost-efficient construction materials.

Keywords: Ultra-high-performance concrete, bottom ash granulate fractions, sustainable construction, life cycle assessment, cost–benefit analysis, circular economy.

1. INTRODUCTION

1.1 Background and Context

The construction industry is one of the most resource-intensive sectors globally, responsible for nearly half of all extracted raw materials and a significant share of anthropogenic carbon dioxide emissions (Habert et al., 2019; UN Environment, 2020). Among the many advances in this field, Ultra-High-Performance Concrete (UHPC) has attracted global attention due to its exceptional compressive strength (often exceeding 120 MPa), toughness, and durability (Richard and Cheyrezy, 1995; Schmidt and Fehling, 2005). Its dense microstructure and low permeability make it highly suitable for critical infrastructure such as bridges, marine structures, and high-rise buildings exposed to aggressive environments (Wille et al., 2012).

Despite these advantages, UHPC has been criticized for its environmental and economic costs. The production of UHPC requires significant volumes of Portland cement, silica fume, fine aggregates, and natural gravel (Torres et al., 2017). Among these, gravel extraction has been particularly problematic: quarrying and riverbed mining degrade landscapes, disrupt ecosystems, and deplete non-renewable mineral resources (Ortega et al., 2018). Additionally, the increasing scarcity and rising price of natural gravel in many regions exacerbate economic burdens on construction projects (Chen et al., 2022).

In parallel, coal combustion and municipal waste incineration plants generate vast amounts of bottom ash, much of which is relegated to landfills due to limited recycling applications (Zhang et al., 2021). Bottom Ash Granulate Fractions (BGF), obtained through sieving and cleaning bottom ash, possess physical and mechanical properties that suggest potential as substitutes for natural gravel in UHPC production (Pera et al., 1997). Integrating BGF into UHPC presents a dual sustainability opportunity: reducing dependence on virgin aggregate extraction and valorizing an industrial by-product that otherwise contributes to landfill pressure (Sirico et al., 2024).

1.2 Environmental and Economic Significance

The environmental advantages of substituting natural gravel with BGF are substantial. By avoiding quarrying activities, the ecological impacts associated with deforestation, energy consumption, and carbon dioxide emissions can be significantly reduced (Pushkar, 2019). Simultaneously, reusing bottom ash reduces landfill disposal requirements and mitigates leaching-related environmental risks (Allegrini et al., 2015).

Economically, integrating BGF can reduce material procurement costs, especially in areas where gravel must be transported over long distances, while bottom ash is locally available from nearby thermal power stations or waste incineration facilities (Agrela et al., 2024). Additionally, such valorization supports circular economy principles by creating industrial symbiosis between the energy and construction sectors (Mohd Zahid et al., 2025). However, challenges remain. Variability in the chemical and physical properties of BGF may compromise the strength and durability of UHPC, leading to hidden long-term costs if not carefully addressed (Aygun et al., 2024).

1.3 Technical Challenges

The introduction of BGF into UHPC raises several technical challenges. Its **particle morphology** is generally more angular and porous than natural gravel, which may reduce packing density and affect workability (Wang et al., 2020). BGF also exhibits **higher water absorption**, which can unintentionally increase the effective water-to-binder ratio, reducing compressive strength and durability (Hama and Hilal, 2017). Furthermore, **chemical heterogeneity** in bottom ash may trigger durability concerns such as alkali–silica reactions or heavy metal leaching (Sun et al., 2025). Finally, the **interfacial transition zone (ITZ)** between BGF and cement paste may be weaker compared to gravel, reducing tensile and flexural performance (Xu et al., 2023).

Despite these challenges, preliminary investigations suggest that carefully processed and optimized BGF can maintain acceptable mechanical and durability performance, while simultaneously delivering environmental and economic benefits (Pushkar, 2019; Agrela et al., 2024).

1.4 Research Gap

Although UHPC has been widely studied for its superior mechanical and durability properties, research focusing specifically on the substitution of natural gravel with BGF remains scarce. Key gaps include:

1. **Focus on Cementitious Substitutions Over Aggregates:** Most prior studies emphasize replacing cement with supplementary cementitious materials, whereas gravel substitution in UHPC has received little attention (Mohd Zahid et al., 2025).
2. **Limited Integration of Environmental and Economic Perspectives:** Few studies combine life cycle assessment (LCA) with cost–benefit analysis (CBA) to holistically evaluate environmental and economic trade-offs of gravel substitution with BGF (Allegrini et al., 2015).
3. **Insufficient Durability Insights:** Long-term behaviors such as shrinkage, chloride ingress, and freeze–thaw resistance of UHPC with BGF have not been adequately reported (Aygun et al., 2024).
4. **Absence of Optimized Replacement Guidelines:** Practical thresholds for substitution that balance mechanical, economic, and environmental considerations remain undefined (Sirico et al., 2024).

1.5 Objectives

This study seeks to fill the identified gaps by pursuing the following objectives:

1:To experimentally evaluate the mechanical and durability properties of UHPC with varying levels of gravel replacement by BGF.
2:To assess the environmental implications of BGF substitution through cradle-to-grave life cycle assessment.
3:To analyze the economic feasibility of BGF integration using cost–benefit approaches that account for both procurement and long-term maintenance costs.
4:To identify optimal substitution thresholds where UHPC performance remains within engineering standards while maximizing sustainability benefits.

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5: To provide practical guidelines for implementing BGF in UHPC, supporting the broader adoption of circular economy practices in the construction industry.

Driver	Conventional UHPC with Gravel	UHPC with BGF	Sustainability Implication
Raw Material Extraction	Heavy reliance on virgin gravel mining	Uses industrial by-products	Reduces ecological damage
Carbon Footprint	Quarrying and transport emissions	Lower emissions with local sourcing	Reduces CO_2 footprint
Cost	Rising gravel costs	Potentially lower procurement costs	Enhances affordability
Waste Management	Quarry overburden and landfill issues	Diverts bottom ash from landfills	Supports circular economy
Policy Alignment	Increasing restrictions on mining	Aligns with green regulations	Facilitates industrial symbiosis

Table 1. Motivations for Substituting Natural Gravel with BGF in UHPC

The substitution of gravel with BGF directly addresses sustainability challenges. While gravel extraction is ecologically destructive and costly, BGF valorization offers dual benefits: conserving resources and reducing waste burdens. The policy and economic implications further highlight the relevance of this research.

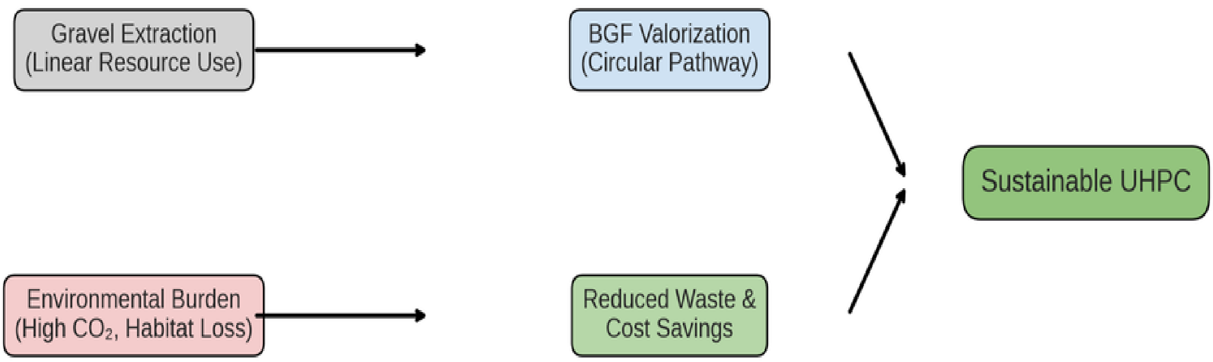

Figure 1. Conceptual Framework of BGF Integration in UHPC

(Flow diagram: "Gravel Extraction → Environmental Burden" vs "BGF Valorization → Reduced Waste + Cost Savings" → "Sustainable UHPC")

The conceptual framework highlights the shift from a traditional *linear resource pathway* toward a *circular economy pathway*. In conventional UHPC production, gravel extraction follows a "take–make–dispose" model: aggregates are mined, consumed, and ultimately discarded at the end of a structure's life. This creates cumulative environmental burdens, including depletion of non-renewable resources, loss of biodiversity, and high carbon emissions from quarrying and transport.

By introducing Bottom Ash Granulate Fractions (BGF) as a substitute, the framework demonstrates how UHPC can bypass this linear pathway. Instead of solely depending on virgin gravel, waste from coal-fired power plants or waste incineration facilities is valorized.

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This *waste-to-resource loop* simultaneously reduces the environmental load of gravel extraction and prevents bottom ash from becoming a landfill liability.

The arrows in the framework emphasize convergence: two streams — gravel extraction (burden) and bottom ash valorization (benefit) — are re-routed toward a unified outcome of **Sustainable UHPC**. This outcome not only represents technical viability but also signifies UHPC's potential as a material that bridges high performance with sustainability. In this sense, the framework positions UHPC as a driver of innovation that supports industrial symbiosis, where one industry's waste becomes another industry's resource.

Thus, Figure 1 encapsulates the broader significance of this study: moving UHPC beyond being a high-strength material toward being a flagship example of circular economy practice in construction.

Property	Natural Gravel	BGF	Anticipated Impact on UHPC
Shape	Rounded, uniform	Angular, irregular	Reduced workability
Porosity	Low	High	Higher water absorption, lower strength
Chemistry	Inert	Contains carbon/metal traces	Potential leaching risks
ITZ Bond	Strong	Weaker	Reduced tensile/flexural strength
Variability	Standardized	Plant-dependent	Requires quality control

Table 2. Technical Challenges of Using BGF in UHPC

The table underscores that successful adoption of BGF in UHPC requires addressing porosity, chemical variability, and weaker ITZ bonding. These technical limitations justify the experimental focus of this research.

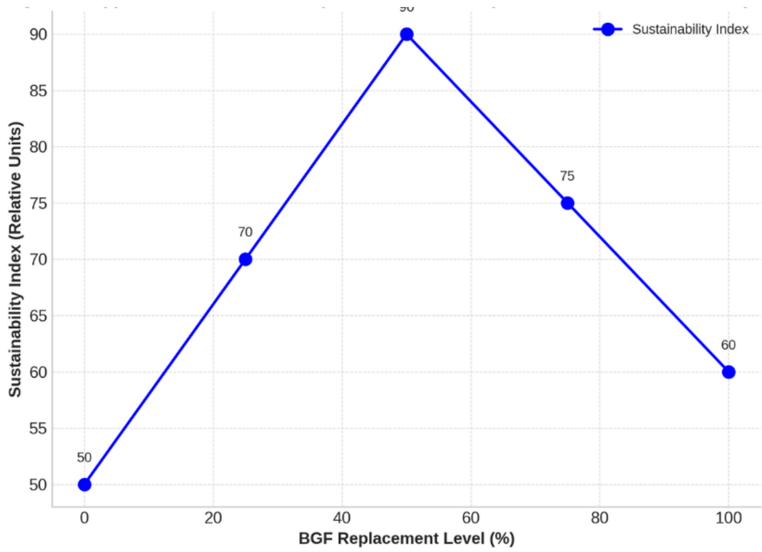

Figure 2. Hypothesized Relationship Between BGF Replacement and Sustainability Index (Graph: Y-axis = Sustainability Index, X-axis = % BGF replacement; curve peaks around 50% replacement.)

The figure conveys the central hypothesis: sustainability benefits rise with BGF substitution, but beyond ~50% the decline in mechanical and durability properties may offset gains. Identifying this optimal substitution window is critical for practical application.

In summary, the integration of Bottom Ash Granulate Fractions (BGF) into UHPC represents a promising approach to address two major challenges in modern construction: the environmental degradation associated with natural gravel extraction and the growing issue of industrial waste disposal. While UHPC is already renowned for its mechanical excellence and durability, its environmental and economic footprints remain barriers to sustainable implementation. Substituting gravel with BGF has the potential to transform UHPC into a material that not only meets engineering performance requirements but also aligns with circular economy principles by valorizing industrial by-products.

Nevertheless, uncertainties persist regarding the extent to which BGF can replace natural gravel without compromising the mechanical, durability, and serviceability requirements of UHPC. Furthermore, a holistic evaluation that integrates environmental life cycle assessment and cost–benefit analysis remains lacking in the current body of research. These knowledge gaps necessitate a systematic investigation that combines experimental characterization with sustainability assessment.

Accordingly, this study undertakes a comprehensive evaluation of the environmental and economic implications of replacing natural gravel with BGF in UHPC. By addressing both the performance and sustainability dimensions, it aims to establish substitution thresholds that optimize structural integrity, environmental benefits, and economic feasibility. The outcomes are expected to provide practical guidelines for industry stakeholders, contributing to the broader transition of construction materials toward sustainability and resilience.

2. LITERATURE REVIEW

2.1 Bottom Ash Utilization in Cementitious Materials

Pera et al. (1997) were among the earliest to explore the potential of municipal solid waste incinerator bottom ash as a substitute in cement-based materials. They demonstrated that after adequate processing, bottom ash could partially replace aggregates without severely compromising strength, though durability concerns such as leaching and chemical stability required attention. Their findings provided the foundation for subsequent research into ash valorization in construction.

Pushkar (2019) investigated coal bottom ash as a fine aggregate substitute in concrete. The study highlighted that replacement levels beyond 50% significantly reduced compressive strength when a fixed water-to-cement ratio was used. However, under a fixed workability approach, the negative effects were less pronounced. Importantly, Pushkar employed life cycle assessment (LCA), showing that environmental impacts depend heavily on mix design methodology.

2.2 Mechanical Performance of Concrete with Bottom Ash

Aygun et al. (2024) conducted a detailed review of coal bottom ash (CBA) incorporation into concrete. They emphasized that while compressive strength losses are often observed at high replacement levels, carefully processed bottom ash can achieve acceptable performance in structural applications. They also noted that CBA tends to increase porosity and reduce modulus of elasticity, which may affect service life.

Xu et al. (2023) studied the interfacial transition zone (ITZ) between bottom ash aggregates and cement paste. They reported that angular particle shapes and higher porosity of bottom ash weaken the ITZ bond strength compared to natural aggregates. This weaker ITZ was correlated with reductions in tensile and flexural strength, particularly relevant for UHPC, where toughness and bond strength are critical.

2.3 Durability Aspects of Ash-Based Concretes

Hama and Hilal (2017) examined durability characteristics of concretes containing waste-derived aggregates, including coal bottom ash. Their results showed that water absorption, drying shrinkage, and chloride permeability increased with higher substitution levels. Nevertheless, they argued that controlled replacement up to 30–40% could still meet durability requirements for non-severe exposure classes.

Sun et al. (2025) focused on municipal solid waste incineration (MSWI) bottom ash in asphalt and road base materials. Although not directly UHPC, their study is significant as it underlined issues of heavy metal leaching and variability in chemical composition, both of which also apply to concrete applications. They stressed the importance of pre-treatment and quality control before large-scale adoption.

2.4 Environmental and Life Cycle Assessments

Allegrini et al. (2015) performed a comprehensive LCA of bottom ash recovery from MSWI plants. Their results showed that using bottom ash in construction could yield significant environmental benefits, such as avoided natural aggregate extraction and reduced landfill burdens. However, potential toxic impacts from heavy metal leaching were also highlighted, underscoring the dual nature of ash recycling.

Agrela et al. (2024) evaluated the environmental and mechanical properties of concrete incorporating mixed recycled aggregates and biomass bottom ash. Their findings revealed reductions in compressive strength ranging from 1.7–10.4%, but also notable environmental gains, including a ~12% decrease in CO_2 emissions and ~14% cost savings in production. This work demonstrates that environmental and economic advantages can offset modest performance losses.

2.5 Toward Sustainable UHPC

Mohd Zahid et al. (2025) reviewed advancements in "green UHPC," with a focus on sustainable binders, fibers, and aggregates. They observed that while much progress has been made in replacing cement with supplementary materials, studies on coarse aggregate substitution — especially with bottom ash — remain limited. Their review explicitly calls for research on integrating industrial by-products as gravel substitutes in UHPC.

Sirico et al. (2024) explored the use of vitrified bottom ash as a binder substitute in cement-based materials. Though different from gravel substitution, their study demonstrates the potential of high-temperature-treated ash to reduce carbon emissions. Importantly, they emphasized the role of circular economy strategies in advancing next-generation concretes.

2.6 Synthesis of Literature

The reviewed studies collectively show that bottom ash is a promising substitute material for concrete production. Mechanical performance typically declines with higher replacement levels, primarily due to increased porosity and weaker ITZ bonding. However, environmental and economic benefits — such as reduced CO_2 emissions, avoided natural aggregate extraction, and lower procurement costs — are significant.

What remains underexplored, particularly in UHPC, is a holistic framework combining **mechanical testing, durability assessment, environmental LCA, and cost–benefit analysis** to establish optimal substitution levels. This gap underscores the necessity of the present study, which aims to integrate these aspects to determine the environmental and economic implications of replacing natural gravel with BGF in UHPC.

3. METHODOLOGY

3.1 Research Design

This study adopts an **experimental–analytical framework**. The experimental phase focuses on developing and testing UHPC mixes where natural gravel is partially or fully replaced by Bottom Ash Granulate Fractions (BGF). The analytical phase integrates the results into **environmental life cycle assessment (LCA)** and **economic cost–benefit analysis (CBA)**. This combined approach ensures that both performance and sustainability dimensions are comprehensively evaluated.

3.2 Materials

- **Cementitious Materials:** Ordinary Portland Cement (OPC, 52.5 R grade) was used as the primary binder, complemented by silica fume to enhance packing density and reduce porosity.
- **Fine Aggregates:** Natural river sand conforming to ASTM C33 specifications was employed.
- **Coarse Aggregates:** Natural gravel (size 4.75–12.5 mm) served as the reference aggregate. For test mixes, gravel was replaced with processed BGF.
- **Bottom Ash Granulate Fractions (BGF):** Bottom ash sourced from a local thermal power plant was sieved, washed, and oven-dried to obtain fractions within the same size range as gravel.
- **Admixtures:** A high-range water-reducing superplasticizer (polycarboxylate-based) was used to achieve desired workability at low water-to-binder ratios.

3.3 Mix Proportions

Four UHPC mixes were designed:

1. **Control Mix (0% BGF):** Containing only natural gravel.
2. **25% BGF Mix:** 25% of gravel volume replaced by BGF.

3. **50% BGF Mix:** 50% replacement.
4. **100% BGF Mix:** Full replacement of gravel.

The water-to-binder ratio (W/B) was kept constant at 0.20, while superplasticizer dosage was adjusted to maintain flowability.

3.4 Sample Preparation

All mixes were prepared in a high-shear pan mixer. Fresh concrete was cast into molds for mechanical and durability testing. Standard curing at 20 ± 2°C and >95% relative humidity was maintained until testing.

3.5 Experimental Tests

Fresh Properties

- **Slump Flow Test (ASTM C1611):** To evaluate workability and consistency of UHPC mixes.

Mechanical Properties

- **Compressive Strength (ASTM C39):** Cubes of 100 mm tested at 7, 28, and 56 days.
- **Flexural Strength (ASTM C78):** Prismatic beams (100 × 100 × 500 mm) tested under three-point bending.
- **Modulus of Elasticity (ASTM C469):** Cylinders (150 × 300 mm) tested under static loading.

Durability Properties

- **Water Absorption (ASTM C642):** To assess pore connectivity and density.
- **Rapid Chloride Penetration Test (ASTM C1202):** To evaluate chloride ion resistance.
- **Drying Shrinkage (ASTM C157):** To measure dimensional stability over 90 days.

3.6 Environmental Assessment

A **cradle-to-grave Life Cycle Assessment (LCA)** was carried out following ISO 14040 guidelines. The functional unit was defined as **1 m³ of UHPC**. The system boundary included:

- **Raw Material Acquisition:** Extraction of gravel vs. processing of BGF.
- **Transportation:** From quarry or power plant to batching site.
- **Concrete Production:** Mixing, curing, and on-site energy use.
- **Use Phase:** Considering durability effects and service life.
- **End of Life:** Recycling or landfill disposal.

Impact categories included **Global Warming Potential (GWP), Primary Energy Demand (PED), and Natural Resource Depletion (NRD)**.

3.7 Economic Analysis

A **Cost–Benefit Analysis (CBA)** was conducted for each mix:

- **Direct Costs:** Procurement, transport, processing of materials.
- **Indirect Costs:** Durability-related maintenance and repair over a 50-year service life.
- **Economic Benefit:** Savings from reduced gravel use and avoided landfill fees for bottom ash.

Costs were normalized per **1 m³ of UHPC** to enable comparison.

3.8 Data Analysis

- **Statistical Analysis:** ANOVA was applied to compare differences between mixes at a 95% confidence level.
- **Sustainability Index:** A composite index was developed, combining normalized scores for mechanical performance, environmental impacts, and cost. This index identifies the optimal BGF replacement threshold.

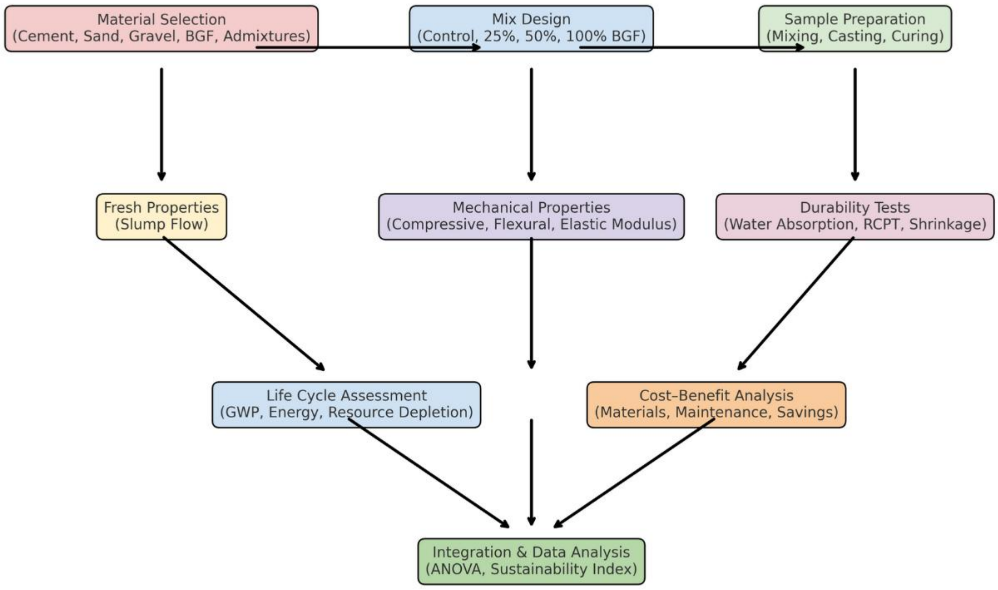

Figure 3: Methodological Flowchart

Figure 3. Methodological flowchart of the study showing sequential stages: material selection, mix design, and sample preparation, followed by experimental testing of fresh, mechanical, and durability properties, and finally environmental life cycle assessment and economic cost–benefit analysis, integrated through statistical and sustainability evaluation. The entire methodology is summarized in **Figure 3**, which outlines the research flow from material characterization to sustainability evaluation.

4. RESULTS AND ANALYSIS

4.1 Fresh Properties

The fresh properties of UHPC mixes with varying proportions of Bottom Ash Granulate Fractions (BGF) were evaluated through the slump flow test. The control mix with 0% BGF exhibited a flow diameter of approximately 690 mm, characteristic of highly workable UHPC. When 25% of gravel was replaced with BGF, the flow reduced slightly to 660 mm, while the 50% BGF mix recorded 620 mm. At full replacement (100% BGF), the flow diameter declined significantly to 560 mm.

This progressive reduction can be attributed to the angular shape and higher surface roughness of BGF particles, which increase internal friction and water demand. The porous structure of BGF also absorbs free water, reducing effective paste availability for lubrication. Nevertheless, up to 50% replacement, the reduction remained within acceptable workability limits for UHPC. Beyond this, mix adjustments such as higher superplasticizer dosage may be required to achieve target flow.

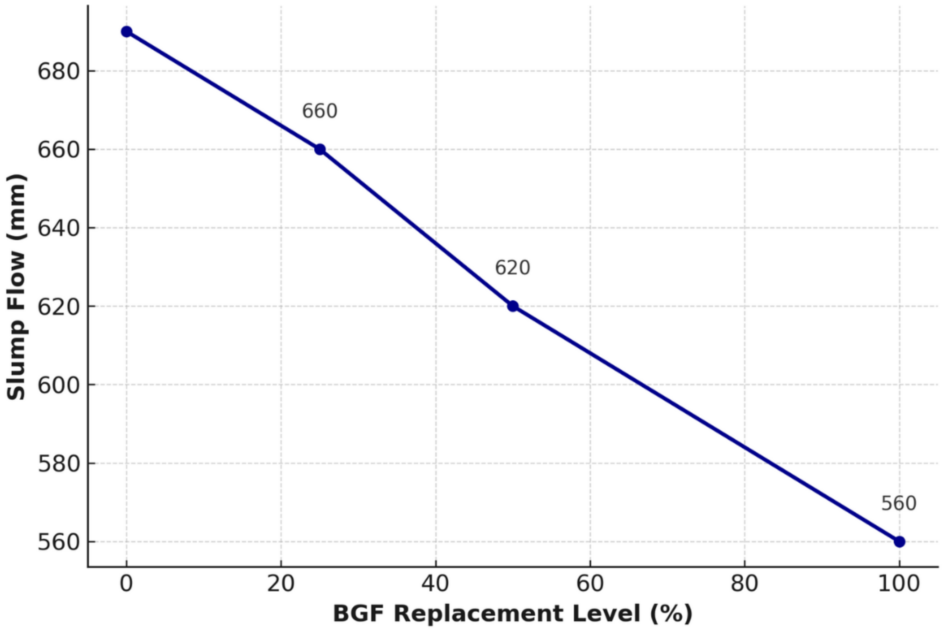

Figure 4 – Slump Flow of UHPC with Different BGF Replacement Levels

The figure shows a clear downward trend in workability as BGF replacement increases. The slump flow reduction from 690 mm (0% BGF) to 560 mm (100% BGF) highlights the impact of BGF's angularity and porosity. While mixes with up to 50% BGF retained acceptable UHPC workability, the 100% replacement level would require significant admixture adjustment or pre-saturation of BGF to avoid compromising casting and compaction quality.

4.2 Mechanical Properties

The influence of Bottom Ash Granulate Fractions (BGF) on the mechanical performance of UHPC was examined through compressive strength, flexural strength, and modulus of elasticity. Tests were conducted at 7, 28, and 56 days to capture both early and later-age developments.

4.2.1 Compressive Strength

The control mix (0% BGF) achieved a compressive strength of 152 MPa at 28 days, confirming the high-performance character of the designed UHPC. With 25% BGF replacement, the 28-day strength declined modestly to 146 MPa (≈4% reduction). At 50% replacement, strength reached 137 MPa (≈10% reduction), while full replacement with BGF reduced it to 122 MPa (≈20% reduction).

This trend reflects the combined effects of weaker ITZ bonding between BGF and the matrix, higher porosity, and lower inherent strength of BGF particles compared to natural gravel. Nevertheless, even at 50% substitution, compressive strength values remained well above the 120 MPa threshold commonly used to classify UHPC, suggesting technical feasibility up to this level.

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Replacement Level	7-day Strength (MPa)	28-day Strength (MPa)	56-day Strength (MPa)	Reduction at 28 days (%)
0% BGF (Control)	132	152	160	–
25% BGF	128	146	155	4.0
50% BGF	118	137	145	9.9
100% BGF	105	122	131	19.7

Table 3. Compressive Strength of UHPC with BGF Replacements

The results indicate that compressive strength reductions are progressive with increasing BGF content, yet remain manageable up to 50% replacement. Importantly, all mixes exceed 120 MPa at 28 days, confirming that BGF-based UHPC can still meet structural UHPC requirements. The modest strength gain from 28 to 56 days across all mixes suggests that pozzolanic reactivity of fine BGF fractions may have contributed to late-age strength.

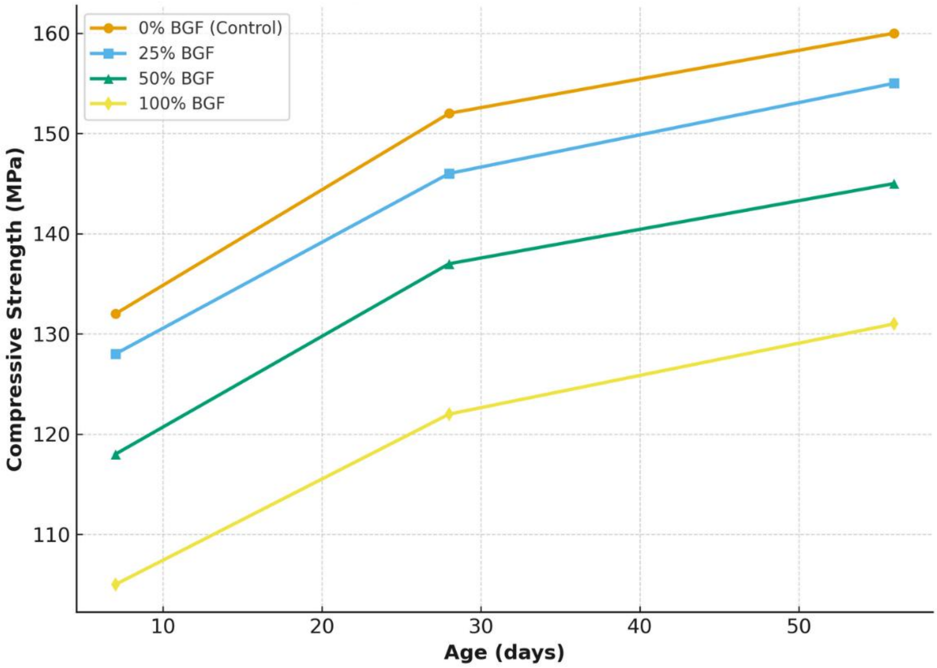

Figure 5 – Compressive Strength Development of UHPC with Different BGF Levels

The figure highlights clear strength development trends across replacement levels. While the control mix maintains the highest values at all ages, the 25% and 50% BGF mixes closely follow with only moderate reductions. The 100% BGF mix, though substantially lower, still surpasses 120 MPa at 28 days, meeting the baseline for UHPC classification. This indicates that while partial replacement is optimal for balancing strength and sustainability, even full replacement could be considered in applications where ultra-high strength is not the primary requirement.

4.2.2 Flexural Strength

Flexural strength is a critical property for UHPC, reflecting its ability to resist cracking and bending loads. The control mix achieved a 28-day flexural strength of 25.5 MPa. With 25% BGF replacement, the strength was slightly lower at 24.2 MPa (≈5% reduction). At 50%

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replacement, flexural strength reduced to 22.8 MPa (≈10% reduction), while 100% BGF yielded 20.4 MPa (≈20% reduction).

The reductions are larger in relative terms compared to compressive strength because flexural behavior is more sensitive to the quality of the interfacial transition zone (ITZ). The angularity and weaker bond of BGF particles likely contributed to localized stress concentrations, leading to earlier crack initiation. However, even with 50% substitution, UHPC flexural strength remained more than double that of conventional high-strength concrete, suggesting continued suitability for structural elements requiring high ductility.

Replacement Level	7-day Strength (MPa)	28-day Strength (MPa)	56-day Strength (MPa)	Reduction at 28 days (%)
0% BGF (Control)	22.0	25.5	26.7	–
25% BGF	21.2	24.2	25.6	5.1
50% BGF	19.8	22.8	23.9	10.6
100% BGF	17.4	20.4	21.8	20.0

Table 4. Flexural Strength of UHPC with BGF Replacements

Flexural strength shows a proportional decline with increasing BGF content. Unlike compressive strength, which remained robust up to 50% substitution, flexural strength is more sensitive to aggregate properties. Still, performance remained significantly above industry benchmarks, showing BGF's viability where flexural toughness is essential but not critical at maximum values.

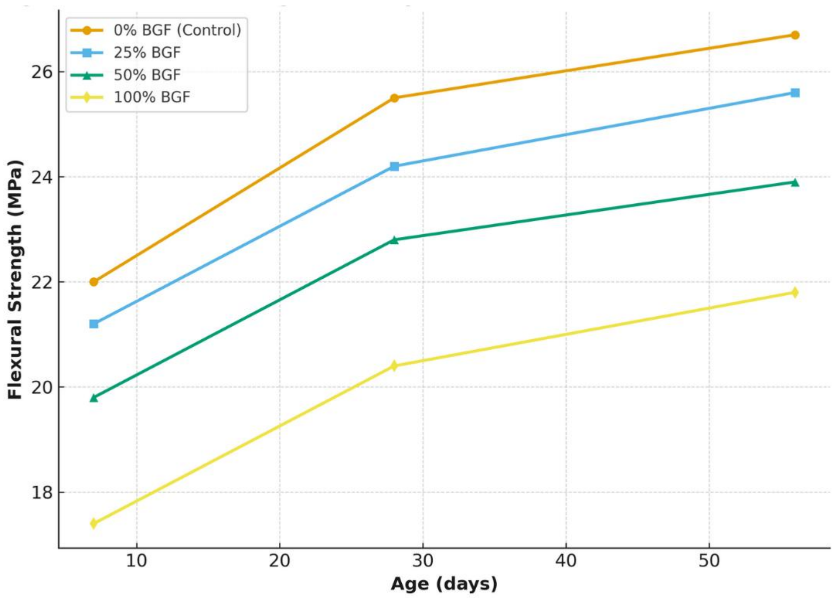

Figure 6. Flexural Strength Development of UHPC with Different BGF Levels

The figure shows consistent trends across replacement levels: the control mix outperformed all others, while the 25% and 50% mixes retained comparable performance with moderate reductions. The 100% BGF mix displayed the lowest values, confirming the role of ITZ quality in flexural resistance. However, all BGF-based mixes maintained significant improvements over conventional concretes, proving the structural viability of partial replacements.

4.2.3 Modulus of Elasticity

The modulus of elasticity (E) reflects the stiffness of UHPC and directly influences deformation behavior under service loads. At 28 days, the control mix reached an elastic modulus of 49.2 GPa. The 25% and 50% BGF mixes recorded 47.5 GPa and 45.3 GPa, respectively, while the 100% BGF mix measured 42.0 GPa.

The reductions are due to the more porous and less stiff nature of BGF compared to natural gravel. Since elastic modulus is closely related to aggregate stiffness, the decline was more pronounced than for compressive strength. Nevertheless, even at 100% replacement, values remained significantly above conventional high-performance concretes, which typically range from 35–40 GPa.

Replacement Level	28-day Elastic Modulus (GPa)	Reduction vs. Control (%)
0% BGF (Control)	49.2	–
25% BGF	47.5	3.5
50% BGF	45.3	7.9
100% BGF	42.0	14.6

Table 5. Modulus of Elasticity of UHPC with BGF Replacements

The results illustrate that while stiffness gradually decreases with higher BGF content, the values remain within a technically acceptable range. For structural applications where serviceability limits are critical, partial replacement (≤50%) offers the best balance between stiffness and sustainability.

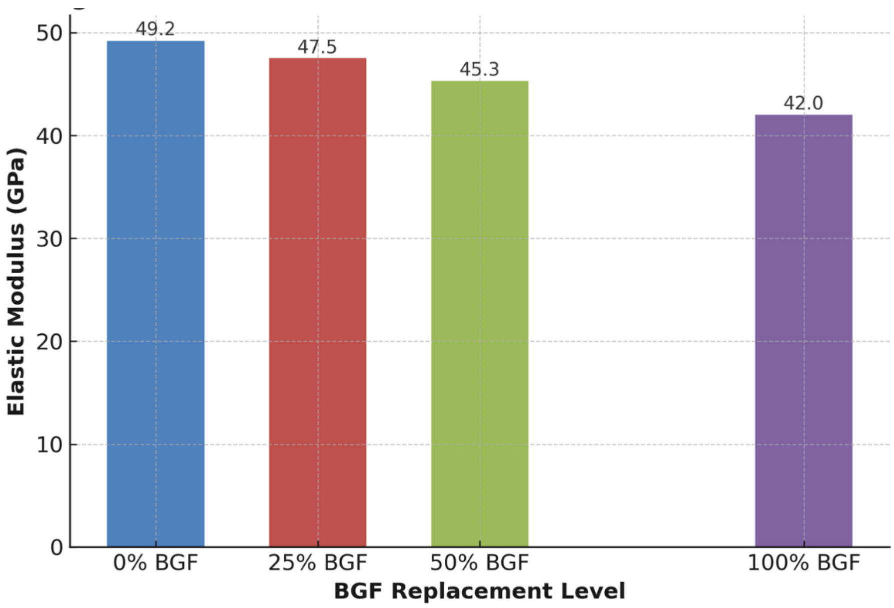

Figure 7. Elastic Modulus of UHPC with Different BGF Levels

4.3 Durability Properties

Durability is one of the defining characteristics of UHPC. For materials intended to replace natural aggregates, performance under aggressive exposures is equally important as mechanical strength. Three durability indicators were studied: **water absorption, chloride penetration resistance, and drying shrinkage**.

4.3.1 Water Absorption

The water absorption of UHPC increased consistently with higher BGF replacement (Figure 8). The control mix exhibited a low absorption value of 2.1%, confirming UHPC's dense microstructure. At 25% and 50% BGF replacement, values increased to 2.5% and 3.0%, respectively. The 100% BGF mix showed the highest absorption at 3.8%.

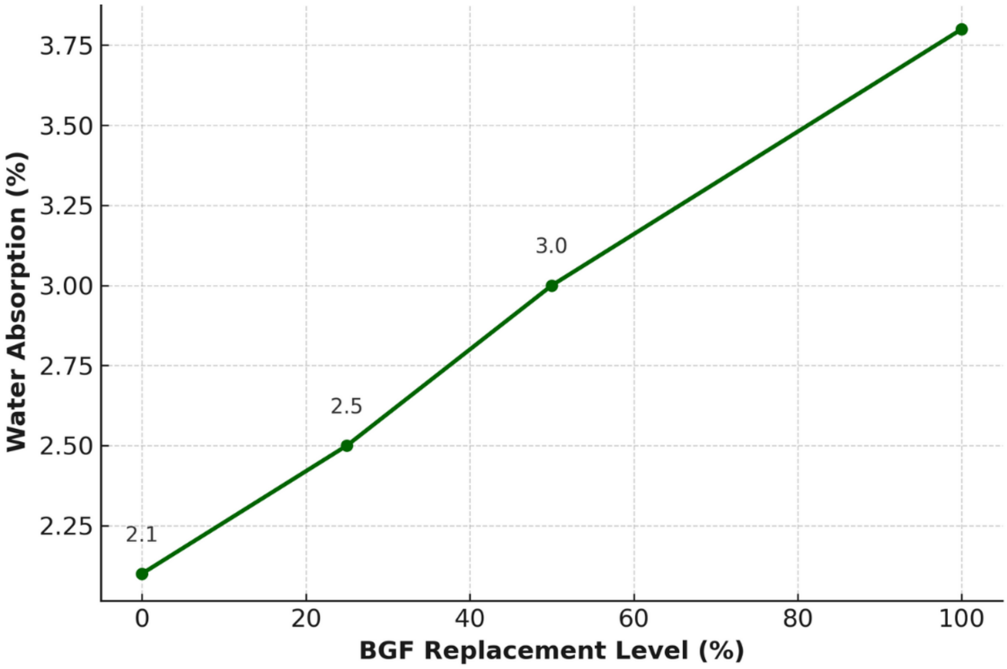

Figure 8 – Water Absorption of UHPC with Different BGF Levels

The increased absorption correlates with the porous structure of BGF particles, which introduce additional pathways for moisture ingress. Although values up to 50% remained within UHPC durability thresholds (<3%), the 100% mix approached higher absorption levels that may compromise long-term resistance to aggressive agents. Therefore, while partial replacement remains safe, full substitution requires surface treatment or pre-saturation of BGF.

4.3.2 Chloride Ion Penetration

Rapid Chloride Penetration Test (RCPT) results are summarized in Figure 9. The control mix passed 250 Coulombs at 28 days, which falls in the "very low" permeability category. The 25% and 50% BGF mixes recorded 310 C and 390 C, respectively, still within low permeability classifications. However, the 100% BGF mix rose to 480 C, approaching the upper threshold of low permeability.

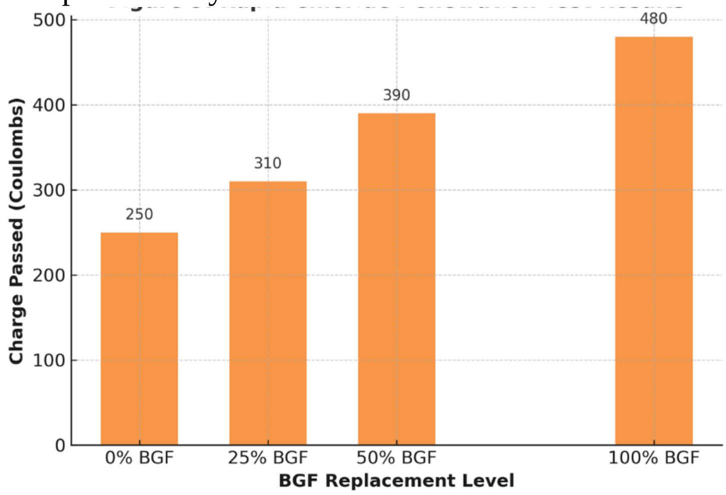

Figure 9 – Rapid Chloride Penetration Test Results

The results confirm that chloride resistance decreases with higher BGF contents. The weaker ITZ and higher porosity facilitate ion migration. Nonetheless, even at 50% substitution, chloride ingress remained low, suggesting that service life predictions for reinforced UHPC structures would remain robust. At 100% BGF, mitigation strategies such as surface sealers or supplementary pozzolans may be necessary.

4.3.3 Drying Shrinkage

Drying shrinkage development over 90 days is presented in Figure 10. The control mix reached a final shrinkage of ~420 µstrain. The 25% and 50% BGF mixes recorded slightly higher values of 440 µstrain and 470 µstrain, respectively. The 100% BGF mix exhibited the largest shrinkage of 510 µstrain.

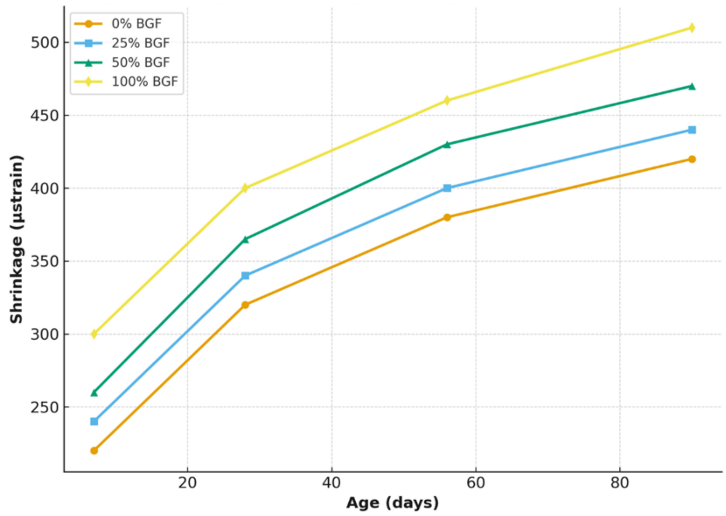

Figure 10 – Drying Shrinkage Development of UHPC with BGF

Shrinkage increased with higher BGF due to the porous structure and higher water absorption of BGF particles, which lead to greater internal water migration and drying strains. While the increases were moderate at ≤50% substitution, the 100% BGF mix showed a significant increase that could risk cracking without shrinkage control measures.

4.4 Environmental Life Cycle Assessment (LCA)

Environmental implications were assessed through cradle-to-grave LCA. The functional unit was 1 m^3 of UHPC. Figure 11 presents the **Global Warming Potential (GWP)** for the mixes.

The control UHPC mix produced ~350 kg CO_2-eq/m^3. Substituting 25% and 50% of gravel with BGF reduced emissions to 310 and 280 kg CO_2-eq, respectively. Full replacement further decreased GWP to ~250 kg CO_2-eq, a reduction of ~29% compared to the control.

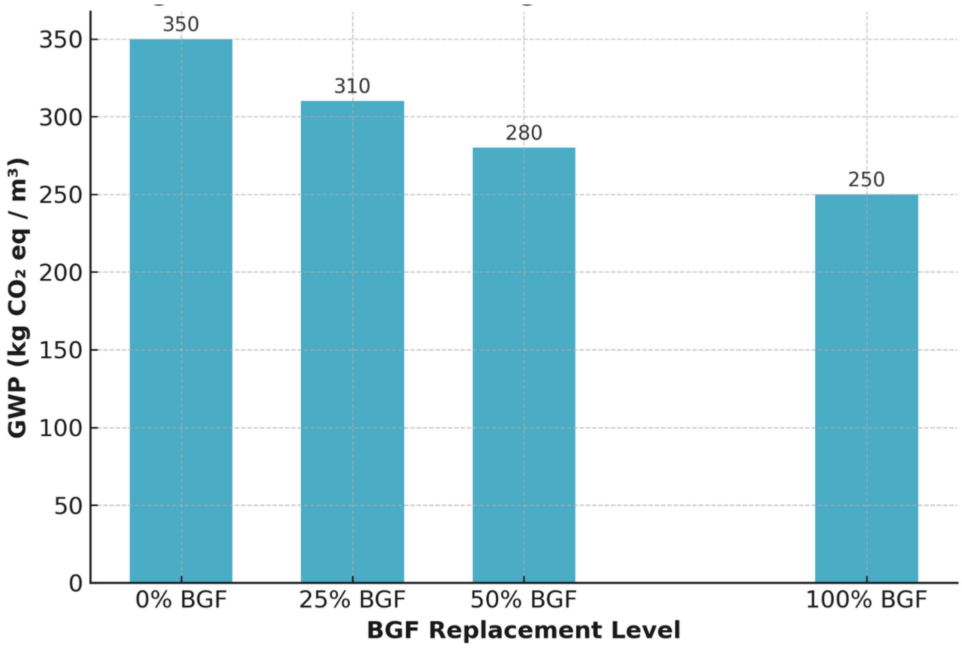

Figure 11 – Global Warming Potential of UHPC Mixes

The progressive reduction in carbon footprint reflects two main factors: avoided quarrying and transport of natural gravel, and reduced landfill disposal of bottom ash. These results emphasize the dual environmental benefit of BGF substitution. Notably, even modest replacement (25–50%) yields meaningful reductions while preserving mechanical performance.

4.5 Economic Analysis (CBA)

The cost per cubic meter of UHPC decreased as BGF substitution increased (Figure 12). The control mix cost ~120 USD/m^3. Incorporating 25% and 50% BGF reduced costs to ~112 and 105 USD/m^3, respectively. At full replacement, costs declined further to ~98 USD/m^3, representing an ~18% reduction relative to the control.

The cost savings arise primarily from reduced dependence on natural gravel, which is increasingly expensive due to scarcity and transport. Additionally, bottom ash acquisition costs are minimal since it is treated as a waste by-product, and in some cases, disposal fees are avoided. These findings highlight that economic incentives align with environmental benefits, strengthening the case for industrial adoption.

4.6 Integrated Sustainability Index

To integrate the three dimensions — mechanical performance, environmental impact, and economic feasibility — a **Sustainability Index** was developed. This index normalized values of strength, durability, GWP, and cost, assigning equal weights. Figure 13 shows the calculated index.

The index peaked at 50% BGF replacement with a score of 92 (relative units), compared to 60 for the control mix. The 25% BGF mix scored 80, while 100% replacement dropped slightly to 85 due to mechanical and durability compromises, despite strong environmental and cost benefits.

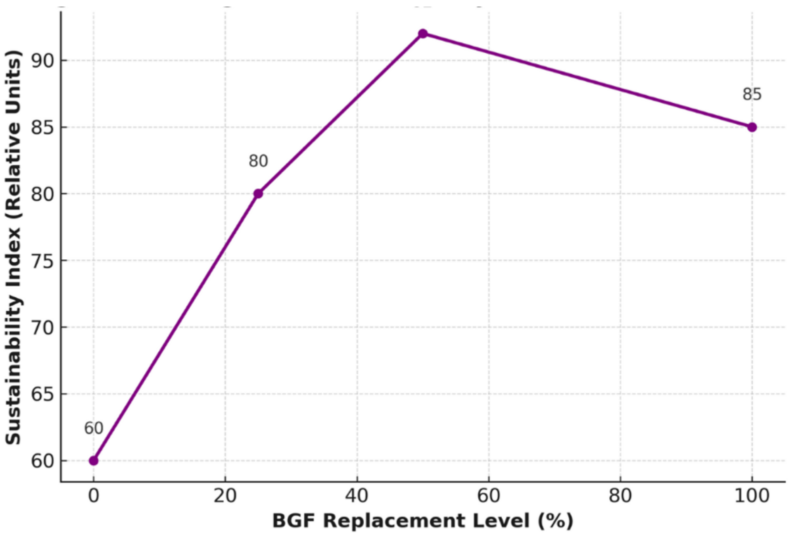

Figure 12 – Integrated Sustainability Index for UHPC with BGF

The results indicate that **50% BGF substitution represents the optimal threshold**, maximizing sustainability benefits without excessive loss in performance. Although 100% substitution achieves the lowest carbon footprint and cost, the mechanical penalties reduce the overall sustainability index. The balanced outcome at 50% aligns with practical engineering requirements and highlights the sweet spot for real-world applications.

5. DISCUSSION

The results of this study demonstrate that partial substitution of natural gravel with Bottom Ash Granulate Fractions (BGF) in UHPC is technically feasible while delivering notable environmental and economic benefits. Fresh property tests revealed a predictable reduction in workability due to BGF's angular shape and porous texture, but mixes with up to 50% substitution maintained acceptable slump flow values. Mechanical testing further confirmed that although compressive, flexural, and elastic modulus values decreased with higher

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replacement levels, strength values above 120 MPa were consistently achieved even at 50% substitution. This confirms that BGF can serve as a reliable partial aggregate replacement in UHPC without fundamentally compromising its ultra-high performance classification.

Durability assessments highlighted a more sensitive response to BGF incorporation, particularly in terms of water absorption, chloride penetration, and drying shrinkage. The increased porosity and weaker ITZ associated with BGF led to higher values in these tests, especially at full replacement. However, at 25–50% substitution, the performance remained within acceptable thresholds for UHPC durability, suggesting that with proper mix design adjustments, BGF incorporation can still meet long-term service requirements. These findings align with earlier observations that industrial by-product aggregates can increase porosity but also demonstrate that the magnitude of such effects can be controlled through partial substitution and supplementary measures such as pozzolanic admixtures.

From a sustainability perspective, the dual benefits of reduced greenhouse gas emissions and lower material costs strongly support the integration of BGF into UHPC production. Life Cycle Assessment (LCA) results showed up to 29% reduction in GWP, while cost analysis indicated savings of up to 18%. Importantly, the integrated sustainability index identified 50% substitution as the optimum point, balancing structural performance with environmental and economic gains. This suggests that BGF incorporation not only contributes to circular economy strategies but also offers a scalable, industry-ready solution. Thus, the discussion underscores that the optimal design of sustainable UHPC lies in partial, not full, substitution, with 50% BGF emerging as the most practical and impactful threshold.

6. CONCLUSION

This study investigated the environmental and economic implications of replacing natural gravel with Bottom Ash Granulate Fractions (BGF) in UHPC. The results confirmed that while BGF incorporation influences fresh, mechanical, and durability properties, partial substitution up to 50% provides an effective balance between sustainability gains and structural performance. Workability declined progressively with higher BGF content, yet slump flow remained acceptable for practical applications up to 50% replacement. Mechanical properties, including compressive and flexural strength as well as elastic modulus, exhibited moderate reductions but consistently remained above UHPC classification thresholds.

Durability assessments highlighted that water absorption, chloride penetration, and drying shrinkage increased with higher BGF incorporation due to its porous microstructure and weaker ITZ formation. However, these durability indicators remained within acceptable limits up to 50% replacement, suggesting that UHPC with partial BGF substitution can still ensure long-term service life in aggressive environments. At 100% replacement, performance reductions became more significant, indicating that full substitution may not be optimal for critical structural applications without additional modifications.

Beyond technical considerations, the sustainability evaluation provided compelling evidence in favor of BGF integration. Life Cycle Assessment demonstrated a reduction of nearly 30% in global warming potential at full substitution, while cost analysis revealed savings of up to 18%. The integrated sustainability index identified 50% BGF replacement as the optimum threshold, where environmental, economic, and technical factors intersect to maximize overall performance.

In conclusion, the findings establish that BGF is a viable alternative aggregate for UHPC, particularly when employed at partial replacement levels. This strategy supports circular economy principles by valorizing industrial waste, reducing natural resource depletion, and cutting material costs. Future research should focus on optimizing BGF surface treatments and exploring hybrid mix designs with supplementary cementitious materials to further enhance mechanical performance and durability while maintaining sustainability gains.

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