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Original Article

Assessing the Environmental Sustainability of UHPC in Modern Construction Practices

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ABSTRACT

A comprehensive examination was undertaken to investigate various aspects related to the development and application of Ultra-High-Performance Concrete (UHPC). The research explored eco-friendly approaches, such as incorporating supplementary cementitious materials and nanoparticles, optimizing binder systems, and assessing chemical activators. These modifications improved mechanical properties and reduced environmental impact, including embodied CO2 emissions. Additionally, the utilization of waste materials like CRT glass showed energy savings and reduced emissions. Studies focused on optimizing UHPC mix designs, emphasizing a balance between performance and environmental impact. Techniques like statistical mixture design methods and dynamic testing assessed UHPC's environmental and economic impacts, highlighting significant energy savings and reduced CO2 emissions with waste material recycling. Overall, the research contributes valuable insights into UHPC development and its ecological footprint in construction.

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INTRODUCTION

The environmental sustainability of Ultra-High-Performance Concrete (UHPC) in contemporary construction practices is being assessed, addressing the intersection of innovative material science and ecological consciousness [1]. UHPC, renowned for its exceptional mechanical properties and versatility, has become a focal point in the quest for sustainable construction materials. This evaluation encompasses diverse dimensions, ranging from raw material selection to the production process and the ultimate environmental impact throughout the life cycle of UHPC [2].

Studies have scrutinized the environmental implications of UHPC by employing Life Cycle Assessment (LCA) methodologies, aiming to quantify the ecological footprint associated with its production and application [3]. These assessments consider factors such as energy consumption, greenhouse gas emissions, and resource utilization, providing a comprehensive view of UHPC's environmental profile.

The incorporation of supplementary cementitious materials, waste by-products, and nanomaterials in UHPC formulations emerges as a pivotal strategy for minimizing its environmental footprint [4]. The use of industrial by-products like fly ash, ground granulated blast furnace slag (GGBS), and metakaolin to partially replace traditional cement, thereby reducing CO_2 emissions and curbing the demand for virgin materials, has been explored.

Furthermore, advancements in mix design optimization play a pivotal role in achieving a balance between mechanical performance and environmental impact. The quest for the optimal combination of constituents, whether through statistical mixture design methods or compressible packing models, seeks to enhance UHPC's efficiency, ensuring that stringent performance criteria are met while minimizing material consumption.

Beyond the production phase, the durability and longevity of UHPC structures contribute significantly to their overall sustainability. The inherent strength and resilience of UHPC translate into an extended service life, mitigating the need for frequent repairs or replacements and, consequently, reducing the environmental burden associated with maintenance activities A comparative study on mechanical properties and environmental impact of UHPC with belite cement and portland cement.

Challenges, however, persist, particularly in addressing the economic feasibility and widespread adoption of UHPC. Cost considerations, both in terms of raw materials and production processes, remain critical factors influencing the material's sustainability. Avenues to reduce costs, such as utilizing locally sourced materials and optimizing mix designs for economic efficiency, are actively being explored by researchers [5].

In essence, the assessment of UHPC's environmental sustainability represents a nuanced exploration of its potential to reshape modern construction practices. Through an interdisciplinary approach that integrates material science, engineering, and environmental considerations, UHPC aims to be propelled beyond being a technological marvel to a cornerstone in the construction industry's commitment to greener and more sustainable practices.

METHODOLOGY

This study aimed to comprehensively examine the development and application of UHPC, with a focus on mechanical properties, microstructure, environmental impacts, and sustainability. The methodology involved a thorough literature review using academic databases like Scopus, Google Scholar and Web of Science, with keywords including "Ultra-High-Performance Concrete," "UHPC," "mechanical properties," "environmental impact," and "sustainability." Articles were screened based on relevance to UHPC development and environmental assessments, prioritizing studies on supplementary cementitious materials, mix design optimization, and dynamic performance evaluations. Data were synthesized to identify trends, challenges, and opportunities in the field, particularly in reducing environmental impact while enhancing mechanical properties. Environmental impact assessments, mix design optimization analyses, and discussions on

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dynamic performance were conducted to quantify UHPC's environmental footprint and improve its sustainability. Statistical analysis methods were employed to optimize mix designs for flowability, compressive strength, and economic efficiency. The study's findings underscored the multifaceted considerations in UHPC development and its potential to reshape modern construction practices towards greener solutions.

FINDINGS

Assessment of the Sustainability Potential of Concrete and Concrete Structures Considering their Environmental Impact, Performance and Lifetime

The sustainability potential of concrete and concrete structures is assessed based on three key parameters: environmental impact, technical performance, and lifetime. It is noted that a reduction in environmental impact during construction is insufficient without ensuring equivalent technical performance and lifetime [6]. Sustainability potential is expressed as a dimension of time multiplied by factors such as strength, divided by parameters like Global Warming Potential (GWP).

Two main approaches are pursued to improve concrete sustainability: reducing environmental impact through lower cement content and developing ultra-high-performance concretes for enhanced durability. While reducing cement content can significantly decrease environmental impact, it may limit strength and durability unless carefully balanced [7]. UHPCs benefit from superior durability but may require additional materials like steel fibres, offsetting some environmental gains. Assessing sustainability involves correctly evaluating concrete's lifetime, considering environmental and mechanical influences compared to its resistance. Service life design quantifies concrete durability in terms of failure probabilities, offering a more precise evaluation method than descriptive standards.

Development of UHPC Mixtures from an Ecological Point of View

The investigation in this study focuses on the substitution of cement in UHPC with less energy-intensive latent hydraulic concrete additives, with an emphasis on their impact on mechanical properties and environmental categories. The study [8] excludes the consideration of production-related CO_2 emissions of these alternative additives, as their environmental impact is already accounted for in their industrial processes. The key findings can be summarized as follows:

When comparing environmental impact categories between UHPC and Normal Strength Concrete (NSC), it is noted that the substitution of cement with Supplementary Cementitious Materials (SCMs) represents an initial step in enhancing UHPC sustainability from an ecological standpoint. However, when considering building components, along with reduced material consumption, increased durability, and extended lifetime, the overall environmental profile is substantially improved. To enhance the environmental standing and competitiveness of Ultra-High-Performance Fibre-Reinforced Concrete (UHPFRC), further optimization of partial cement substitution and exploration of alternative fibre materials are deemed necessary.

Design and Preparation of UHPC with Low Environmental Impact

A balance between UHPC performance and environmental impact can be achieved by preparing low carbon emission UHPC with only 20-25% cement in the total binder system, utilizing multi-scale reactive mineral powders like fly ash, slag, silica fume, and nano-SiO_2 effectively [9].

The strength of UHPC with low cement content is significantly improved by nano-SiO_2, albeit with a slight increase in embodied carbon emissions. The performance of UHPC is influenced by chemical activators, with sodium sulphate identified as the most effective in improving

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strength and reducing the embodied CO_2 index. Steam curing and autoclave curing enhance mechanical properties, with autoclave curing deemed more suitable for low carbon emission UHPC.

Analysis of the environmental impact index indicates that chemical activators and heat curing are effective methods for producing sustainable UHPC, while nanotechnology strategies are less satisfactory. Combining the chemical activation method with heat curing synergistically reduces carbon intensity and enhances the environmental sustainability of UHPC. The embodied CO_2 index of UHPC decreases, and the embodied CO_2 increases gradually with increasing strength. The study successfully prepares low carbon emission UHPC with an embodied CO_2 emission index of no more than 4 kg/MPa·m^3, contributing to significantly lower carbon emissions compared to conventional UHPCs, regardless of compositions and curing regimes.

Development of an Eco-friendly UHPC with Efficient Cement and Mineral Admixtures Uses

In this paper [10], an environmentally friendly UHPC is formulated and evaluated. The following conclusions are drawn from the results: A modified Andreasen & Andersen particle packing model is used to produce UHPC with different mineral admixtures (FA, GGBA, and LP). The comparison of embedded CO_2 emissions with other UHPCs indicates that the proposed methodology allows the production of eco-friendly concrete with a relatively low environmental impact.

Environmental and Economical Friendly UHPC Incorporating Appropriate Quarry-Stone Powders

To address the issue of low cement hydration levels and mitigate the environmental risks associated with quarry stone powder, the inclusion of quarry stone powders in UHPC production, replacing 22.2% – 44.4% of cement, is examined, and the properties of the modified UHPC are assessed [11]. The key findings are as follows:

The embedded CO_2 calculation for the designed UHPC indicates that reducing the amount of unhydrated cement by incorporating quarry stone powders into UHPC production is considered environmentally and economically reasonable. Therefore, quarry stone powder emerges as a suitable industrial waste solid for producing sustainable UHPC [4]. In comparison to basalt stone powder, limestone powder is identified as a more suitable substitute to replace cement in manufacturing UHPC with advanced mechanical properties, high volume stability, good durability, and low environmental impacts. This presents a novel approach to producing cleaner products in the future [12], [13].

Statistical Mixture Design Approach for Eco-efficient UHPC

An effective mixture design method has been developed for environmentally friendly UHPC and is presented in this work, utilizing a statistical mixture design (SMD) approach [14]. Specifically, the newly proposed model focuses on minimizing UHPC cement dosage while maintaining its compressive strength. The regression model, employing a D-optimal design, comprehensively analyses UHPC properties within the chosen range of constituents. The adequacy of the polynomial regression model is confirmed by lack-of-fit test results and high coefficients of multiple determinations (R_2), demonstrating its capability to predict the desired performance of UHPC.

Critical review on Eco-efficient UHPC Enhanced with Nanomaterials

In this paper [15], a comprehensive review is presented regarding two fundamental aspects crucial for the design of eco-efficient UHPC. UHPC is defined by exceptional mechanical and durability properties, coupled with a significantly reduced environmental impact compared to traditional UHPC. The following conclusions are derived from an extensive literature survey on various UHPC mix design approaches and the incorporation of Supplementary Cementitious Materials (SCMs):

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The compressible packing model (CPM) concept, forming the basis of most UHPC mix design methods, has limitations, especially when dealing with UHPC mixtures containing constituents of different sizes. Moreover, these models may not accurately predict the behaviour of UHPC with very fine particles due to the neglect of surface forces such as van der Waals forces, electrical charges, and steric forces [2]. Methods based on UHPC rheology are found to be simple and accurate for predicting UHPC properties [16]. However, these methods lack definitive guidelines for optimizing constituent dosages to ensure both high flowability and high compressive strength.

Statistical mixture design (SMD) methods are deemed efficient not only in predicting UHPC performance but also in optimizing constituent proportions. These methods can incorporate considerations of curing type and utilize numerical approaches with multi-objective functions to design UHPC mixtures achieving high compressive strength, minimal Portland cement dosage, and predefined flow properties [4]. However, many proposed mixture design methods necessitate extensive testing and numerous trial batches.

Partial replacement of silica fume (SF) and Portland cement with supplementary cementitious materials like fly ash (FA), ground granulated blast furnace slag (GGBS), metakaolin (MK), and rice husk ash (RHA) enables the production of UHPC with comparable mechanical and durability properties [5]. These SCMs effectively reduce the high autogenous shrinkage of UHPC. However, many studies assume UHPC mixture proportions rather than optimizing them, raising questions about whether the mixture proportion is genuinely optimized and if the binder is used efficiently.

Durability and Microstructure of Eco-Efficient UHPC

The following conclusions were drawn from the laboratory results and observations obtained from tests conducted on the UHPC specimens [17]: Sustainability enhancement by replacing 30% of the cement weight is evident, but a more substantial improvement is achieved with a 50% replacement, emphasizing the goal of maintaining ultra-high-performance behaviour.

Slightly lower compressive strength is exhibited by UHPC mixtures using CEM III as the primary binder compared to mixtures using CEM I, with a disadvantage of 11.4%. Optimal sulphate attack resistance is achieved with 50% fly ash (FA) replacement, resulting in a compressive strength decrease to 157.4 MPa after 180 days of sulphate attack with a sulphate concentration of 75 g/l.

To maintain ultra-high performance with specimens subjected to 180` days of sulphate attack, sulphate concentrations should not exceed 50 g/l, and replacement percentages of 50% and 30% for CEM III and granulated blast furnace slag (GBFS), respectively. With a sulphate concentration of 75 g/l, a 5% increase in silica fume (SF) leads to a negligible 5.8% improvement in compressive strength, while a 10% SF increase improves strength by 12.4%, compared to samples with 15% SF content. Replacing cement with 30% FA slightly improves UHPC resistance to chloride penetration by 8%. Increasing replacement to 50% results in increased chloride penetration depth but remains less than the controlling mixture. CEM III is slightly better in chloride resistance than GBFS. For mixtures with CEM III as the main binder, replacing up to 50% FA with an increase in SF content from 15% to 25% improves UHPC resistance to chloride penetration, with a slight 9.2% decrease in penetration depth relative to the control mix. FA replacement increases cement hydration in UHPC at later ages, leading to substantial pozzolanic reactions that improve the UHPC microstructure.

A New Development of Eco-Friendly UHPC: Towards efficient Steel Slag Application and Multi-Objective Optimization

In this study [18], an optimized mix design for environmentally friendly UHPC is achieved using a mathematical method (DOD), ensuring the simultaneous optimization of multiple objectives and efficient utilization of steel slag in the UHPC system. The key findings are as follows: The study

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establishes regression models based on DOD to simulate UHPC properties (workability, voids ratio, and compressive strength) in relation to raw materials. The models demonstrate excellent ANOVA results, with high accuracy correlation coefficients (R2 > 0.95) and significant P-values (less than 0.05), confirming the feasibility of predicting UHPC performance using polynomial regression models.

The global desirability function is employed to optimize the design of a new UHPC with multiple objectives, including maximum workability and compressive strength, minimum voids ratio, and the highest steel slag content. This approach successfully designs and produces a new UHPC with excellent properties, featuring relatively high workability (268 mm), impressive compressive strength (131 MPa), low voids ratio (0.148), and a substantial steel slag content (200 kg/m^3). The addition of SSP (steel slag powder) enhances UHPC workability without compromising mechanical properties and does not impact the types of hydration products. It is noteworthy that the chloride penetration resistance of UHPC may decrease with SSP incorporation but remains superior to that of ordinary concrete. The newly developed UHPC with relatively low cement content and high steel slag content demonstrates outstanding ecological value in engineering. Specifically, the optimized UHPC exhibits lower energy consumption and emissions compared to other alternatives, positioning it as a green and cleaner concrete product.

Eco-efficient UHPC Development by Means of Response Surface Methodology

In this research paper [19], a statistical mixture design method based on Response Surface Methodology (RSM) was employed to develop an eco-efficient UHPC. Two models concerning flow diameter and compressive strength, characterized by small P-values, insignificant lack of fit, and closely adjusted/predicted R-squared values, were proposed. The primary factor contributing to reduced flowability was identified as sand, while silica fume, accounting for up to 9% of cement weight, initially increased the flow diameter before displaying a slight negative impact. Ultra-Fine Fly Ash (UFFA), constituting up to 43% of cement weight, demonstrated a positive effect on both flow diameter and compressive strength, with marginal impacts at higher percentages. This indicated the potential of UFFA, as an industrial waste material, to serve as a substitute for cement and silica fume in UHPC formulations. Silica fume played a crucial role in compressive strength development, while sand exhibited a negative effect when exceeding 145% of cement weight.

Numerical optimization for two responses was conducted under various scenarios and importance weights. The numerical solutions closely aligned with experimental results, highlighting the high efficiency of RSM in UHPC development. Based on these findings, an eco-efficient UHPC with reduced cement and silica fume content (640 kg/m^3 and 56.3 kg/m^3, respectively) was formulated.

Comparative Analysis of Mechanical Properties and Environmental Impact of UHPC variants

A comparative study [5] was conducted to evaluate the mechanical properties and environmental impact of two types of Ultra-High-Performance Concrete (UHPC): one with belite cement (UHPC-BC) and the other with Portland cement (UHPC-OPC). Lower environmental impact indices were demonstrated by UHPC-BC compared to UHPC-OPC, with a compressive strength of 197.5 MPa achieved after 90 days of autoclave curing and an embodied carbon of 934.37 kg/m3. This suggests promising applications of belite cement in precast concrete production, particularly in eco-friendly UHPC formulations.

In another study [20], the feasibility of manufacturing UHPC using aeolian sand was investigated, and its mechanical properties and environmental impact were evaluated. The mix proportions for UHPC were determined based on modified particle packing theory, and environmental impact was assessed using ECI and UCI indexes. Lowering the water/binder ratio

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improved the environmental impact of UHPC, with a significant negative correlation found between compressive strength and ECI. A steel fibre content of 3.0 vol% was recommended for achieving optimal mechanical properties and balancing environmental impact in UHPC formulations.

Advancing UHPC for Cost-Efficient and Environmentally Sustainable Construction

Valuable insights into the development and application of Ultra-High-Performance Concrete with a focus on cost and environmental sustainability are provided by the reviewed papers [21]. Mechanical properties, microstructure, and environmental impact of UHPC variants are explored, offering promising avenues for eco-friendly construction practices.

A systematic assessment of the life-cycle cost and environmental impacts of UHPC bridges compared to conventional ones is conducted, highlighting a notable reduction in CO_2 emissions and advocating for UHPC's broader application in civil infrastructures [22]. Despite the initial higher construction costs, the extended structural service life of UHPC bridges has proven advantageous, ultimately reducing equivalent annual costs.

The carbon, material, and water footprint of UHPC are evaluated, revealing higher environmental impacts but also potential benefits, particularly in practical applications like bridges [23]. Novel insights into raw material demand and primary material extraction for UHPC underscore the importance of developing policies to maximize its environmental benefits [24].

Research on eco-friendly UHPC variants, such as those incorporating belite cement, aeolian sand, or waste materials like cathode ray tube glass, demonstrates reduced carbon emissions and enhanced mechanical properties [25], [26]. Optimization strategies involving nanoparticles, chemical activators, and modified steel fibres contribute to improved environmental performance and cost-effectiveness [27], [28].

Furthermore, studies on UHPC with low cement content and integrated supplementary cementitious materials emphasize the potential for producing greener and more cost-effective UHPC mixtures without compromising mechanical performance [27]. This approach offers a viable solution for reducing CO_2 emissions per unit volume while maintaining structural integrity. These findings underscore the multifaceted considerations in UHPC development, ranging from mechanical performance and mix design optimization to environmental sustainability. By integrating cost-effective strategies and eco-friendly materials, UHPC presents a promising solution for constructing durable, high-performance structures with minimal environmental impact.

Advancing Environmental Performance Through Life Cycle Assessment of UHPC Structures

Valuable insights into the environmental performance of concrete structures, particularly concerning UHPC, are offered by the reviewed papers through the lens of life cycle assessment (LCA). Firstly, the optimal compressive strength of RHA UHPLC is evaluated alongside its environmental impact. Life cycle assessment reveals that the choice of concrete mix significantly influences environmental performance, with C-300 identified as the optimal option due to its favourable profile [16]. Additionally, AI techniques are employed to predict compressive strength, demonstrating the importance of various factors such as superplasticizer content and cement content in influencing performance.

In another study, the environmental impacts of bridge designs involving Ultra-High-Performance Fibre-Reinforced Concrete (UHPFRC) are compared [29]. The life cycle analysis emphasizes the importance of considering multiple time horizons, including construction, maintenance, and elimination phases. Results show that UHPFRC structures, particularly those incorporating composite timber, exhibit lower environmental impacts compared to conventional reinforced concrete bridges, highlighting the

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potential of UHPC in reducing maintenance-related impacts.

Furthermore, the life cycle assessment of UHPC structures indicates that while they may initially have a higher ecological impact compared to normal concrete, sustainability can be enhanced by reducing Portland cement and micro steel fibre content [30]. Opportunities for more sustainable construction practices are identified through the incorporation of alternative materials like blast furnace slag and inert lime powder, demonstrating the potential for UHPC to contribute to environmentally friendly building practices. The studies underscore the importance of life cycle assessment in evaluating the environmental performance of concrete structures and highlight the potential of UHPC to mitigate environmental impacts through optimization of mix designs and incorporation of alternative materials.

CONCLUSION

In conclusion, the extensive exploration of Ultra-High-Performance Concrete across diverse studies has illuminated a path toward a more sustainable and high-performing future in construction materials. The multifaceted investigations, spanning mechanical properties, mix design optimization, and environmental impacts, collectively underscore the potential of UHPC to revolutionize the construction industry.

Researchers have intricately examined the constituents and formulations of UHPC, striving to strike a delicate balance between mechanical strength, workability, and environmental considerations. The incorporation of supplementary materials, nanoparticles, and waste products not only enhances performance but also significantly reduces the environmental footprint, aligning with the global imperative for eco-friendly construction practices.

Mix design methodologies, ranging from statistical approaches to compressible packing models, have been explored to fine-tune UHPC formulations. The emphasis on achieving optimal combinations for flowability and compressive strength reflects a commitment to efficiency and resource utilization. Moreover, the life cycle assessments have delved into the broader implications of UHPC deployment, considering economic, environmental, and dynamic performance aspects. From recycled waste materials to modified steel fibres, innovative approaches have emerged, paving the way for energy savings, reduced carbon emissions, and enhanced durability.

While UHPC presents a promising avenue for sustainable construction, challenges persist, notably in terms of costs and widespread adoption. As researchers navigate these challenges, the vision of a construction landscape characterized by reduced material usage, minimized environmental impact and heightened durability becomes increasingly tangible. Generally, UHPC is not merely a material but a catalyst for positive change in the construction paradigm. The journey from mechanical properties to mix design optimization and environmental considerations encapsulates a holistic approach toward constructing a more resilient and sustainable future. The findings from these studies collectively contribute to a comprehensive understanding of UHPC's potential, offering a blueprint for transformative advancements in the realm of construction materials and practices.

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