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Research paper

LIFE CYCLE ASSESSMENT OF NOVEL MATERIALS FOR LOW-CARBON CONCRETE PRODUCTION

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Abstract

Concrete is a fundamental material in construction, but its production, particularly the manufacturing of cement as a binding agent, is a significant source of CO_2 emissions, contributing to global climate change. With the continued demand for concrete in infrastructure development, there is an urgent need to identify and implement sustainable, low-carbon alternatives. This study addresses this challenge by evaluating the environmental performance of conventional and emerging low-carbon materials used in concrete production. Using the Life Cycle Assessment (LCA) methodology, we conducted a comparative analysis of multiple concrete mixtures, focusing on their embodied carbon and overall environmental impact. Our findings highlight the potential of novel materials to reduce the carbon footprint of concrete while maintaining structural integrity. This research provides critical insights into the sustainability of low-carbon concrete and offers actionable recommendations for the construction industry to transition toward more environmentally friendly practices.

Key words: *Concrete, Cement, Substantially, Life Cycle Assessment, Environmental Impact.*

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1. INTRODUCTION

Concrete is one of the most broadly utilized building materials globally, playing a critical role in constructing roads, buildings, bridges, and various other infrastructures. On average, around one ton of concrete is produced annually for every person on the planet. Given its widespread use, it is essential to accurately assess the environmental impact of this material [1]. Reducing the use of cement and natural aggregates in concrete production is an effective way to mitigate this impact. Incorporating supplementary cementitious materials (SCMs) as partial replacements for cement could significantly lower the overall CO_2 footprint of the final concrete product. However, the environmental implications of concrete extend beyond cement alone, as aggregates also play a critical role in both resource consumption and waste generation within the construction sector [2,3]. On one hand, aggregates constitute about three-quarters of concrete by volume, making concrete a significant consumer of natural resources. When concrete is demolished after its service life or due to deterioration, it becomes inert waste, often occupying substantial space in landfills [4]. Meanwhile, the massive consumption of aggregates and concrete in construction inevitably results in the generation of waste, specifically Construction and Demolition (C&D) waste. Globally, the total production of C&D waste exceeds three billion tons annually [5]. Greenhouse gas (GHG) emissions occur not only during the manufacturing stage but also throughout the construction process, including construction, operations, maintenance, and the final renovation or demolition stage [6]. The built environment accounts for over 37% of global energy-related CO_2 emissions. In 2021, operational CO_2 emissions from the buildings sector increased by 5% compared to 2020, exceeding the 2019 peak by 2%. Furthermore, construction materials, which currently contribute 9% of total energy-related CO2 emissions, are expected to see their impact double by 2060 [7]. To address climate change and global warming, efforts to reduce carbon emissions are being pursued globally [8]. Growing global environmental awareness and increasing demand for eco-friendly materials are driving the sector toward a sustainability-focused approach. As a result, the industry is gradually adopting materials with lower embodied energy and reduced environmental impact, as well as those better suited to local climate conditions [9]. Reducing CO_2 emissions from cement and concrete production is crucial in advancing climate goals. Decarbonizing these materials could lower carbon intensity and significantly reduce the construction sector's ecological footprint [10]. The integration of alternative materials supports the conservation of natural resources and minimizes waste disposal by incorporating urban and industrial waste into concrete, according to the principles of the circular economy. The environmental benefits of using recycled materials in common building elements are typically assessed through a Life Cycle Assessment (LCA), evaluating primary embodied energy and greenhouse gas emissions based on a “cradle-to-gate” approach [11]. Life-cycle analysis (LCA) involves collecting and assessing the inputs, outputs, and potential environmental impacts of a product system throughout its entire life cycle. This methodology enables the quantification of environmental loads and helps identify key processes that significantly contribute to the overall impact. As a result, LCA serves as a crucial tool in the design and development of materials, products, and systems [12]. In this context, LCA has been widely applied in various studies to investigate the environmental impact of manufacturing construction and building materials, such as cement-based materials [13, 14, 15, 16]. This research aims to assess the sustainability of concrete incorporating pozzolanic materials and to quantify the carbon footprints of several concrete mixes made with alternative materials.

2. DEFINITIONS AND FRAMEWORKS OF LIFE CYCLE ASSESSMENT (LCA)

Sustainability is typically investigated using Life Cycle Assessment (LCA), a key environmental management tool that evaluates the impacts and resource demands of a product or service. By quantifying material and energy consumption, along with waste emissions throughout its lifespan, LCA provides a comprehensive analysis of environmental effects. Although its primary focus is on environmental aspects, its life cycle approach and methodology could be adapted to assess economic and social impacts as well [17]. According to ISO standards, LCA involves four key steps: defining the goal and scope, developing the Life Cycle Inventory, examining environmental impacts, and interpreting the results [18, 19, 20, 21]. The life cycle assessment framework is shown in Figure 1.

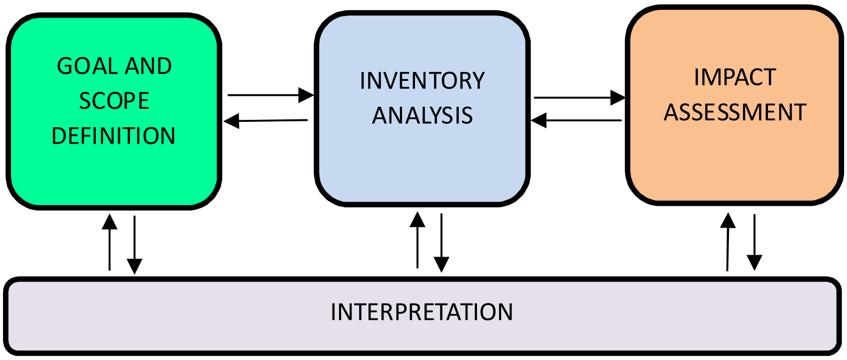

Figure 1. Life cycle assessment Framework [22, 23]

This initial phase involves identifying the assessment's purpose, the intended audience, and the specific questions to be addressed. It also includes defining the system boundaries, which establish what is included in the assessment, such as materials, processes, and transportation, and what is excluded [24]. According to ISO 14044, the system boundary defines which methods are included in the LCA and must align with the study's goal. Like other products, the LCA system boundary for buildings could follow a cradle-to-grave, cradle-to-gate (for building product analysis), or gate-to-gate (for construction process analysis) approach. Typically, the cradle-to-grave approach is used, covering the entire lifecycle from the pre-use phase to the End-of-Life (EOL) phase. The system boundary should also specify spatial and temporal limits, serving as both a research constraint and a benchmark for future studies [25]. In the scope definition, the function and functional unit (e.g., liter, m^2, m^3), system boundaries, data quality requirements, system comparisons, and considerations for critical analyses should be carefully considered and clearly described [26]. This study aims to conduct a cradle-to-gate LCA to evaluate the environmental implications of producing concrete using recycled material and then compare them with reference concrete.

In the Inventory Analysis (LCI) phase, data is gathered on the inputs and outputs of the system under study. This involves quantifying energy consumption, raw material usage, air, water, and soil emissions, and waste generation. Given its data-intensive nature, inventory analysis often requires specialized databases and software tools to systematically compile, manage, and analyze relevant information [24]. The effectiveness of a Life Cycle Assessment

(LCA) considerably depends on the accuracy and completeness of its Life Cycle Inventory (LCI), which gathers data on mass and energy inputs and outputs across all life-cycle stages. Without a reliable and thorough LCI, the LCA's value could be compromised by uncertainties in the subsequent Life Cycle Impact Assessment (LCIA) or by gaps in the environmental impact categories assessed. In short, robust and trustworthy LCAs for concrete production are grounded in well-developed and comprehensive LCIs [27]. The third phase involves evaluating the potential environmental impacts associated with the inputs and outputs identified during the inventory analysis [24]. In this phase, the results from the inventory analysis are investigated to determine their potential environmental impacts. As with the inventory phase, the choice of assessment method and impact categories is guided by the Goal and Scope definition. Most LCA practitioners typically rely on established and published assessment methodologies rather than developing new ones from scratch [28]. The final stage of a Life Cycle Assessment (LCA) involves interpreting the results, where the impact assessment outcomes are analyzed for their robustness and sensitivity to input data. Conclusions are then drawn in alignment with the LCA's original goals and objectives. This stage also includes data validation, which is carried out by comparing findings with existing literature and performing sensitivity analyses to assess the reliability of non-local databases [28].

3. CARBON FOOTPRINT CALCULATION AND REDUCTION FOR CONCRETE MIXES

Concrete is the most widely produced material in the world and has a significant role in the construction industry. However, the environmental impact of traditional concrete production, particularly in terms of carbon emissions and the depletion of natural resources, is a serious concern [29]. Sustainable construction is increasingly being supported by a broader selection of materials considered suitable for use in concrete. This opens up opportunities to incorporate new materials into concrete mix designs. The use of these secondary materials could significantly reduce environmental impacts by lowering energy consumption in cement production, decreasing landfill use, and minimizing the emission of combustion gases [30]. There is also limited potential for reducing CO2 emissions without a greater use of secondary cementitious materials (SCMs) such as FA/GGBS. In addition, Current clinker replacement levels in the UK are just over 13%, with a target of reaching 30% replacement by 2050 [30]. Figure 2 presents the life cycle assessment for concrete from cradle to gate, including three phases and considering measures to mitigate the carbon footprint. The first phase is the extraction and processing of raw materials used in construction, such as cement or concrete. In this stage, important materials include sand, gravel, supplementary cementitious materials (SCMs) like fly ash, rice husk ash (RHA), or slag. These materials are generally obtained from quarries, mines, or industrial by-products. The environmental impact at this stage, particularly regarding CO_2 emissions, is primarily linked to the energy consumed during the mining and processing of these materials. Extraction materials require processes such as drilling, blasting, and crushing, all of which consume diesel and electricity. Moreover, the screening and washing of aggregates such as sand and gravel contribute significantly to energy demand. Even the production or collection of SCMs like fly ash, a by-product of coal combustion, involves emissions from the drying process or transport from power plants. Therefore, in the first stage, the selection and quantity of raw materials directly impact the carbon footprint of the final product. Utilizing locally sourced materials, recycled aggregates, or low-carbon alternatives could significantly reduce emissions during this phase. The second phase involves the movement of raw materials from their extraction sites to the manufacturing facility. This stage primarily contributes to CO_2 emissions through the use of fossil fuel-powered vehicles, such as diesel trucks, which are commonly used to transport heavy construction materials. The environmental impact of this phase is influenced by factors such as distance traveled, mode of transport, fuel type, and load efficiency. In Life Cycle Assessment (LCA) for construction products, it is necessary to accurately capture these details to quantify the overall carbon footprint and environmental impact of the product system. The third phase encompasses all processes that transform raw materials into the final construction product at the factory. It consists of activities such as mixing, processing, casting, and curing concrete, as well as any energy or water used during production. This phase is often one of the most energy-intensive phases of the life cycle, especially for materials like cement, which produce high CO_2 emissions due to both fuel combustion and chemical processes, such as calcination. The concrete mix design is essential as it defines the proportions and types of materials (cement, aggregates, water, admixtures, and SCMs) used to create concrete. Optimizing the concrete mix design by reducing cement content, incorporating supplementary cementitious materials (SCMs), or using effective admixtures could significantly decrease the carbon footprint and resource intensity during the manufacturing stage.

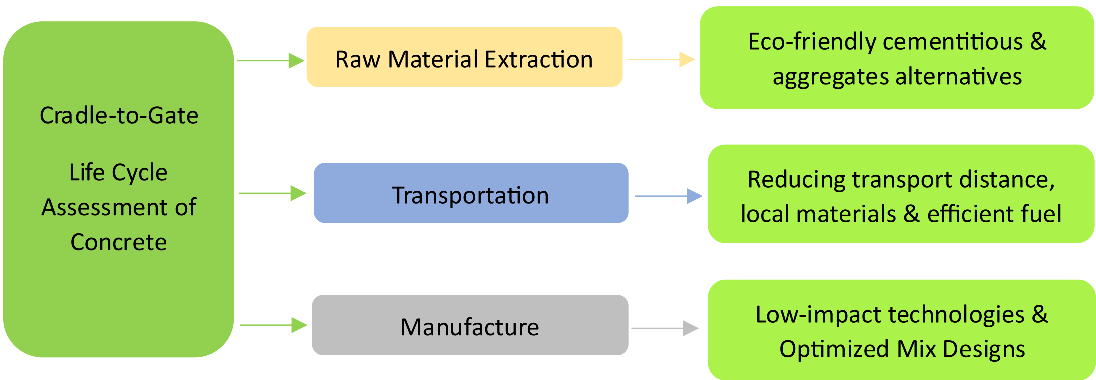

Figure 2. Product Phases (Cradle-to-Gate) of Life Cycle Assessment of Concrete with Potentially Carbon Footprint Mitigation Measures [Author].

To calculate the carbon impact of a concrete mixture, it is necessary to initially determine the quantity of each material used in the mix design. Subsequently, for each constituent, it is necessary to select an appropriate Embodied Carbon ($kgCO_2e/kg$), which accurately reflects its environmental impact. Figure 3 shows CO_2 emissions for the raw materials used in this study.

Each material's quantity must then be multiplied by its corresponding carbon factor to determine the individual carbon impact. Ultimately, the total carbon footprint of the concrete mixture could be obtained by summing the carbon impacts of all constituents [31].

Carbon impact of a concrete mix = ∑ Quantity of each constituent (kg/m^3) × carbon emission factor for constituent (kgCO_2e/kg) (1)

The reduction in carbon emissions between mixes could be calculated by comparing them to a baseline concrete. The calculation of the reduction is as follows [31].

$$\text{Carbon reduction (\%)} = [1- (\frac{\text{Carbon impact of reduced carbon mix}}{\text{Carbon impact of baseline mix}})] \times 100 \quad (2)$$

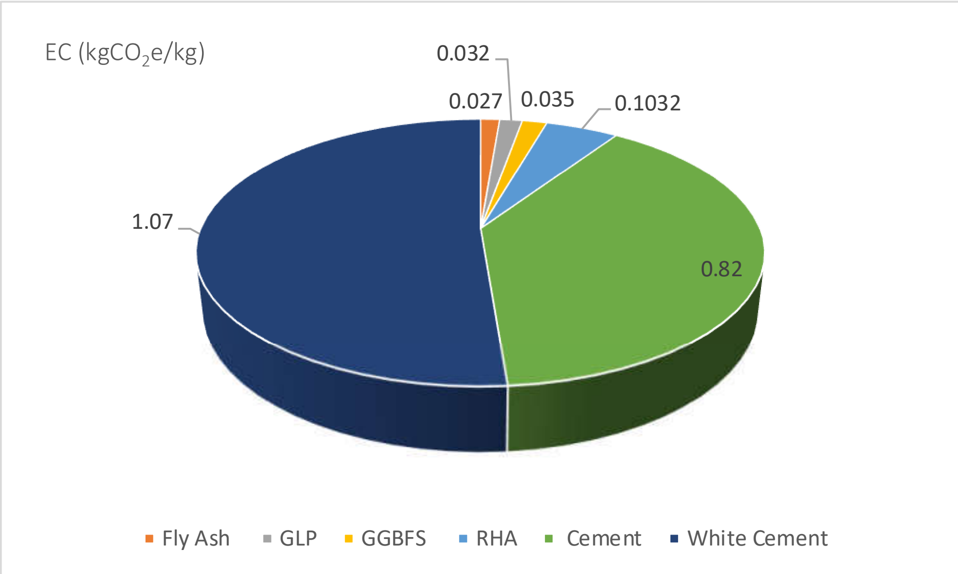

Figure 3. Embodied Carbon (kgCO_2e/kg) of various binder materials based on Table 1. Sources: created based on [32, 33, 34, 35]

4. EVALUATING THE ENVIRONMENTAL IMPACT OF VARIOUS CONCRETE MIXTURES INCORPORATING ALTERNATIVE MATERIALS

Comparisons of the environmental impact of different concrete mixes have been carried out by considering the major parameters as quantities of raw materials required to produce 1 m^3 of concrete. Table 1 provides the raw material quantities required for 1 m^3 of each concrete mix. It presents five different concrete mix designs, each incorporating various combinations of binder and aggregate materials to explore alternative and sustainable compositions. Sample 1 is a conventional mix using only ordinary Portland cement (OPC), while Sample 2 entirely replaces OPC with a blend of fly ash and GGBFS, highlighting a low-carbon approach. Sample 3 combines a reduced amount of OPC with a high proportion of GGBFS, aiming for sustainability. Sample 4 introduces rice husk ash (RHA) as a partial cement replacement, promoting pozzolanic activity. Finally, Sample 5 uses white cement with ground limestone powder. Although white cement has a higher energy demand and carbon intensity than OPC, the inclusion of limestone powder helps mitigate some of the environmental impact. All mixes maintain comparable aggregate and water content to ensure consistency in performance testing.

Table 1. Dosage of concrete components for 1 m³ of concrete. Sources: created based on [36,37,38,39]

Mixture	Cement (kg)	White Cement (kg)	Fly Ash (kg)	GGBFS (kg)	RHA (kg)	Ground Limestone Powder (kg)	Coarse Aggregate (kg)	Fine Aggregate (kg)	Water (kg)
Sample 1	360	0	0	0	0	0	1027	775	180
Sample 2	0	0	150	150	0	0	1365	585	150
Sample 3	90	0	0	270	0	0	1027	775	180
Sample 4	280	0	0	0	70	0	1023	837	140
Sample 5	0	407.9	0	0	0	102.0	1029.7	745.8	158.1

For the concrete mix design presented in Table 1, the CO_2 emission has been calculated according to Formula 1 to assess the environmental impact. For the calculation of CO_2 emission, the basic values of each raw material have been considered in various studies.

Table 2. CO_2 Emission by Raw Materials for $1m^3$ of concrete Sources: created based on [32,33,34,35]

Material's	EC ($kgCO_2e/kg$)	Actual CO_2 Emission from 1 m^3 concrete				
		Sample1 (baseline mix)	Sample 2	Sample 3	Sample 4	Sample 5
Cement	0.82	295.2	0	73.8	229.6	0
White Cement	1.07	0	0	0	0	436.45
Fly Ash	0.027	0	4.05	0	0	0
GGBFS	0.035	0	5.25	9.45	0	0
RHA	0.1032	0	0	0	7.2	0
GLP	0.032	0	0	0	0	3.26
Coarse Aggregate	0.0408	41.9	55.7	41.9	41.7	42.01
Fine Aggregate	0.0139	10.77	8.13	10.8	11.6	10.36
Total Carbon impact of different mixes (kgCO2e/m3)		347.87	73.13	135.95	290.1	492.08

Table 2 displays the CO_2 emissions per cubic meter of concrete for five distinct mix designs, based on individual raw materials' emission coefficients (EC). Sample 1, which consists of a baseline mix utilizing 360 kg of Ordinary Portland Cement (OPC), results in an emission of 347.87 kg CO_2 equivalent per cubic meter ($kgCO_2e/m^3$). Cement is the primary contributor to these emissions, accounting for the majority at 295.2 $kgCO_2e$. Sample 2, which replaces cement entirely with fly ash and GGBFS, demonstrates a remarkable reduction in emissions, reaching just 73.13 $kgCO_2e/m^3$. This makes it an excellent choice for environmentally conscious construction, highlighting its potential as a sustainable alternative. Sample 3, combining 90 kg of OPC and 270 kg of GGBFS, results in emissions of 135.95 $kgCO_2e/m^3$. This level is still below the baseline, indicating a positive step toward reducing overall emissions. Sample 4, which includes rice husk ash (RHA) as a partial replacement, shows a total emissions level of 290.1 $kgCO_2e/m^3$. It's important to note that RHA replaced 20% of the cement by weight, significantly contributing to the reduction of CO_2 emissions. Sample 5 recorded the highest emissions at 492.08 $kgCO_2e/m^3$, primarily due to the use of white cement, which alone contributed 436.45 $kgCO_2e$. While the inclusion of ground limestone powder, which has a low CO_2 emission factor of 0.032 kg CO_2/kg, helps decrease overall CO_2 emissions, the use of white cement, which has a higher emission coefficient compared to ordinary Portland cement (OPC), ultimately results in a significantly larger carbon footprint. This highlights the importance of material selection in minimizing the environmental impact of concrete production. Figure 4. Shows Cradle-to-Gate (A1–A3) Life Cycle Assessment (LCA) approach for comparative analysis of the environmental impacts of various concrete mixes.

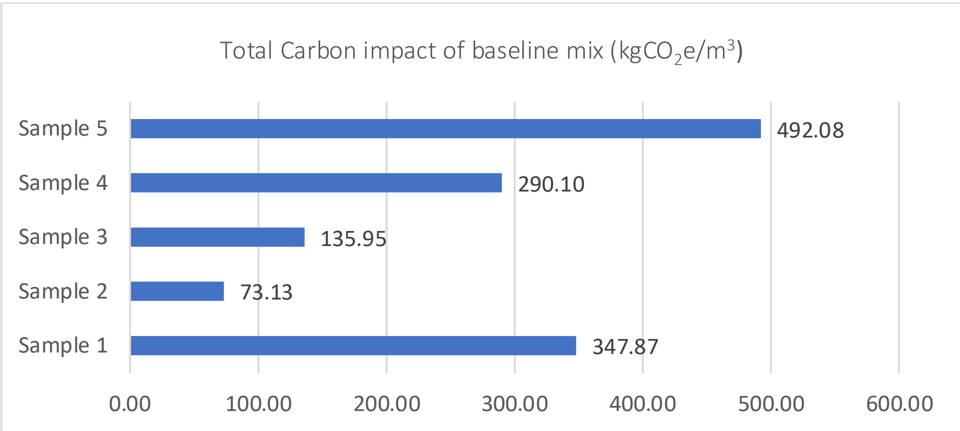

Figure 4. Cradle-to-Gate (A1–A3) Life Cycle Assessment (LCA) approach for comparative analysis of the environmental impacts of various concrete mixes.

Figure 5 illustrates the carbon reduction percentages of various concrete samples relative to a baseline concrete (Sample 1). The baseline exhibits a 0% carbon reduction, serving as the reference point. Sample 2 demonstrates the highest carbon reduction at 78.97%, followed by Sample 3 with a decrease of 60.91%, and Sample 4 with a modest reduction of 16.6%. These samples are indicated with green bars, signifying positive environmental performance. In contrast, Sample 5 exhibits a carbon increase of 41.45% compared to the baseline, as depicted by the red bar, indicating a detrimental impact on carbon emissions. The accompanying table below the chart provides a clear numerical summary of these results. Overall, the figure emphasizes the variability in carbon performance across different concrete formulations, highlighting the serious importance of material selection for sustainable construction.

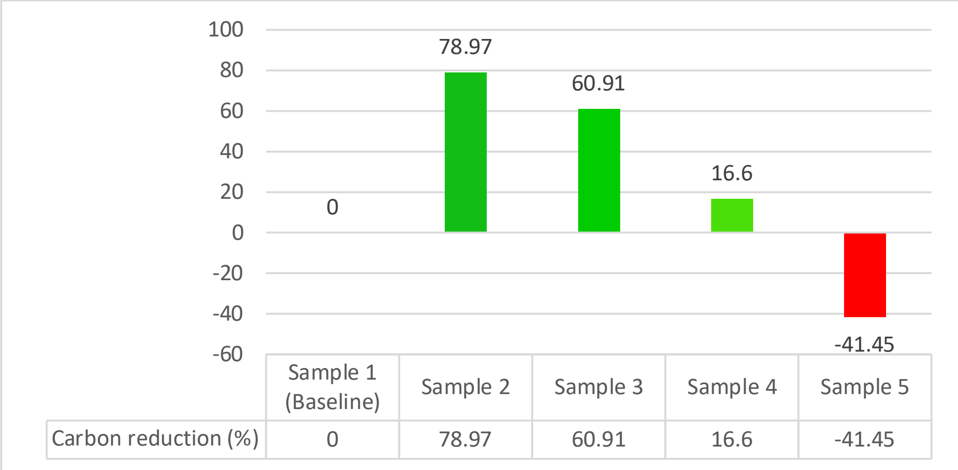

Figure 5. Carbon reduction compared to baseline concrete

5. CONCLUSIONS

In summary, low-carbon concrete is essential for improving sustainable construction and environmental responsibility by reducing carbon emissions and improving resource efficiency. This study highlights the cradle-to-gate embodied carbon emissions of concrete mixtures designed with various binders such as Cement, White Cement, Fly Ash, GGBFS, RHA, GLP, and compares them with each other, showing the way forward in reducing the environmental impact of concrete production to combat climate change. Significant variations in carbon emissions are directly associated with the choice of raw materials in concrete mixtures. The findings from the carbon reduction analysis and CO_2 emission data demonstrate the substantial influence of raw material selection on the environmental performance of concrete. Samples incorporating supplementary cementitious materials, such as ground granulated blast furnace slag (GGBFS), fly ash, and rice husk ash (RHA), exhibited significant reductions in carbon emissions compared to the baseline concrete mix. Specifically, Sample 2 achieved the highest carbon reduction of 78.97%, with the lowest total carbon footprint of 73.13 $kgCO_2e/m^3$, highlighting the effectiveness of using industrial by-products in sustainable concrete design. Sample 4 achieved only a modest reduction (16.6%), mainly because of the limited substitution and the introduction of RHA, while maintaining a moderate total emission level (290.1 $kgCO_2e/m^3$). Conversely, Sample 5, which utilized white cement with a high embodied carbon value (1.07 $kgCO_2e/kg$), led to a 41.45% increase in emissions, reaching a total of 492.08 $kgCO_2e/m^3$. Although ground limestone powder was combined into Sample 5, contributing a relatively low embodied carbon value (0.032 $kgCO_2e/kg$), its positive environmental effect was minimal due to the enormous carbon impact of the high white cement content. Overall, these results emphasize that replacing ordinary Portland cement with suitable alternative binders is significant in dramatically decreasing the carbon footprint of concrete. Careful and balanced selection of materials is essential for advancing the development of low-carbon and environmentally sustainable concrete formulations.

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