

Low-Carbon Cementitious Solutions for Modern Civil Engineering: Experimental Analysis of Concrete Incorporating GGBS and Fly Ash as Partial Cement Replacements

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ABSTRACT

Rapid urbanization and the rising pace of infrastructure development have significantly increased the global demand for construction materials, particularly cement, which is recognized as a major contributor to carbon dioxide emissions. In light of growing environmental concerns, civil engineers and materials scientists are actively exploring sustainable alternatives that reduce the ecological impact of conventional concrete. One promising and widely studied strategy is the partial replacement of Ordinary Portland Cement (OPC) with supplementary cementitious materials like Ground Granulated Blast Furnace Slag (GGBS) and fly ash. These industrial by-products are abundant, cost-effective, and environmentally friendly, offering the dual benefits of waste valorization and improved concrete performance. Their use aligns with the broader objectives of sustainable development and the circular economy in the construction sector. This study presents a detailed experimental investigation aimed at evaluating the mechanical and durability performance of low-carbon concrete incorporating GGBS and fly ash as partial cement replacements. Various concrete mixes were prepared with different substitution levels 10%, 20%, 30%, 40% and assessed through standardized tests for compressive strength, split tensile strength, and flexural strength at curing intervals of 7, 14, and 28 days. These mechanical tests were complemented by durability assessments, including water absorption, sulfate resistance, and acid resistance evaluations, to determine the materials' suitability in aggressive environmental conditions. The mix designs followed established civil engineering practices, ensuring workability and uniformity across samples. The experimental findings indicate that a 30% replacement level provides the most favorable balance between strength and durability. However, higher substitution ratios, particularly at 40%, resulted in significantly enhanced chemical resistance, suggesting potential

applications in corrosive or marine environments. Compared to traditional concrete, the GGBS and fly ash-based mixes exhibited not only improved structural behavior but also a substantial reduction in carbon emissions due to lower OPC content. These blends also showed enhanced microstructural integrity and lower porosity, contributing to their long-term stability. The reduction in OPC consumption directly supports efforts to lower the embodied carbon of construction materials, addressing both environmental and regulatory challenges in the sector. Furthermore, the successful incorporation of industrial waste into structural concrete demonstrates the practical viability of adopting green engineering practices on a large scale. This research affirms the potential of GGBS and fly ash as alternative cementitious materials, offering a durable, cost-effective, and sustainable solution for modern civil engineering infrastructure. The outcomes of this study can assist engineers, contractors, and policymakers in advancing eco-efficient concrete technologies without compromising on performance or structural reliability.

Keywords: Low-carbon concrete, GGBS, Fly ash, Sustainable construction, Cement replacement, Mechanical properties, Durability performance, Industrial by-products, Eco-efficient materials, Civil engineering infrastructure.

Introduction:

Concrete, the most widely used man-made material on Earth, serves as the backbone of global infrastructure from high-rise buildings and bridges to roads and dams. Its ubiquity is due to its versatile mechanical performance, cost-effectiveness, and adaptability to various construction environments. Central to concrete's formulation is Ordinary Portland Cement (OPC), which acts as the binding agent for aggregates. However, while OPC is structurally indispensable, its production is highly energy-intensive and contributes significantly to greenhouse gas emissions, primarily carbon dioxide (CO₂) [1]. The cement industry is responsible for an estimated 7–8% of global CO₂ emissions, stemming from both the calcination of limestone and the combustion of fossil fuels required to reach the high kiln temperatures of approximately 1450°C. This dual impact places cement production among the top contributors to anthropogenic climate change. As urbanization intensifies, especially in emerging economies, the global demand for cement continues to rise. According to the International Energy Agency (IEA), cement production reached 4.3 billion metric tons in 2022, and projections indicate steady growth to support expanding cities and infrastructure development. This creates an urgent challenge: how can we continue to meet construction demands without accelerating environmental degradation? One compelling approach lies in reducing the clinker factor in cement-based materials by substituting OPC with Supplementary Cementitious Materials (SCMs) particularly industrial by-products that would otherwise contribute to environmental waste. Among these SCMs, Ground Granulated Blast Furnace Slag (GGBS) and fly ash have emerged as two of the most effective and widely researched alternatives. GGBS is a by-product of the iron and steel manufacturing process, obtained by rapidly cooling molten slag to produce a glassy, granular material that is then ground to a fine powder. It exhibits latent hydraulic properties, allowing it to react with water and calcium hydroxide to form cementitious compounds [2]. Fly

ash, on the other hand, is a fine particulate residue collected from the combustion of pulverized coal in thermal power plants. Rich in silica and alumina, fly ash is a pozzolanic material, reacting with the calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C-S-H), the primary contributor to concrete strength. The beneficial properties of GGBS and fly ash include improved long-term strength, reduced heat of hydration, enhanced resistance to sulfate and acid attack, and a more refined microstructure that lowers concrete porosity. In addition to technical advantages, their use provides significant environmental benefits, such as lower embodied carbon, reduced energy consumption, and the valorization of industrial waste, which aligns with the principles of a circular economy and sustainable development. To highlight their comparative benefits, a summary of the physical, mechanical, and environmental performance characteristics of GGBS and fly ash is presented in table 1 below.

Table 1: Comparative Properties of GGBS and Fly Ash as Partial Replacements for OPC

Property	Ground Granulated Blast Furnace Slag (GGBS)	Fly Ash
Source	Steel industry (blast furnace slag)	Thermal power plants (coal ash)
Reactivity Type	Latent hydraulic	Pozzolanic
Key Components	CaO, SiO ₂ , Al ₂ O ₃ , MgO	SiO ₂ , Al ₂ O ₃ , Fe ₂ O ₃
Effect on Strength	Improves long-term strength	Moderate early strength, better later
Heat of Hydration	Low	Low
Chemical Resistance	High (sulfate & acid)	Moderate to high
CO ₂ Emission Reduction Potential	Up to 90% (per kg cement replaced)	Up to 70%
Availability	Moderate to high	High in coal-intensive regions
Influence on Workability	Improves	May reduce slightly (type-dependent)

The environmental imperative is further underscored by global CO₂ emission data. As shown in the following figure 1, cement manufacturing is a significant emitter globally, with Asia accounting for more than 70% of total cement-related CO₂ emissions. This makes the integration of SCMs particularly relevant in high-growth economies.

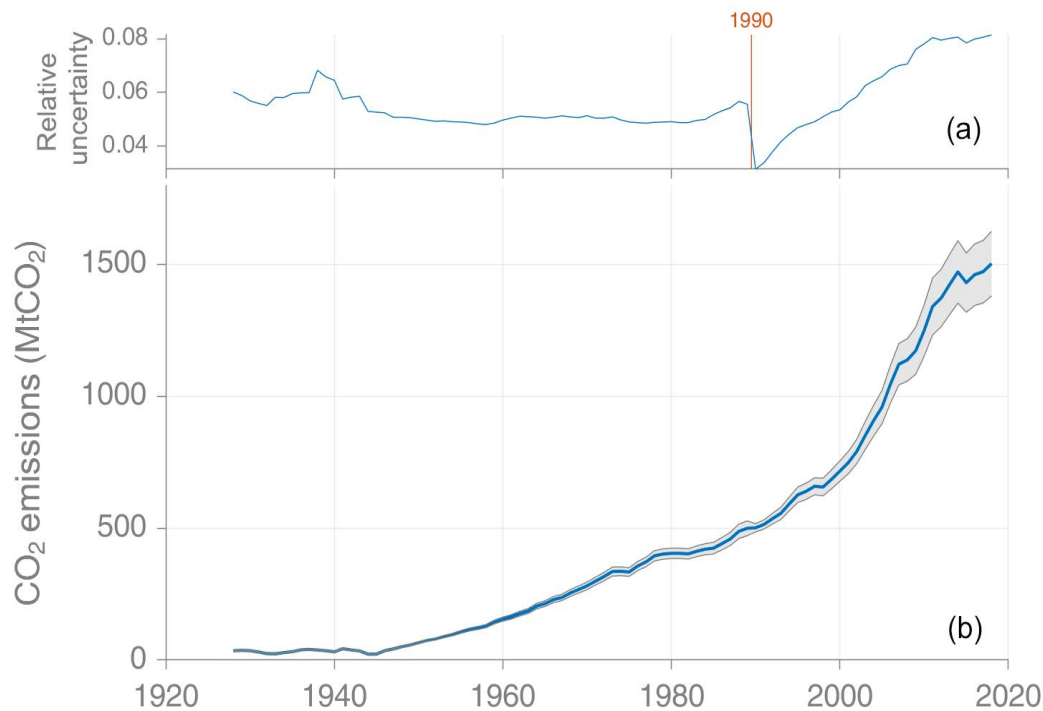


Figure 1: Estimated Global CO₂ Emissions from Cement Production.

This study aims to address both the environmental and technical aspects of modern concrete design by investigating the mechanical and durability performance of concrete mixes in which OPC is partially replaced with GGBS and fly ash. The primary objective is to evaluate various concrete mixes containing 10%, 20%, 30%, and 40% of GGBS and fly ash as replacement levels and determine the optimal proportion that achieves both strength efficiency and durability under diverse curing conditions. The research methodology involves casting standardized concrete specimens and testing them for compressive strength, split tensile strength, and flexural strength at curing ages of 7, 14, and 28 days [3]. Additionally, durability assessments, including water absorption, acid resistance, and sulfate resistance, are conducted to evaluate performance under potentially aggressive environments, such as those found in marine or industrial zones. All concrete mix designs and tests follow international standards including ASTM C39/C496/C78 and IS 456:2000, ensuring that results are comparable with global benchmarks. The findings from this research will help quantify the reduction in embodied carbon, identify optimum replacement ratios, and validate the long-term structural performance of low-carbon concrete. Beyond academia, this knowledge can inform the decisions of civil engineers, contractors, and policymakers working toward eco-efficient construction practices in both public and private sectors [4]. Ultimately, this study contributes to the growing body of evidence that GGBS and fly ash are not merely alternatives to OPC, but essential components of next-generation sustainable concrete technologies. Their incorporation into mainstream construction practice represents a viable and impactful pathway toward low-carbon infrastructure, reinforcing the engineering community's role in addressing climate change through innovative material science.

Conventional Concrete and Its Carbon Footprint:

Concrete is the most widely used construction material globally due to its versatility, durability, and relative cost-efficiency. At the heart of concrete lies Ordinary Portland Cement (OPC), which serves as the primary binding material. However, the production of OPC is an energy-intensive process that contributes significantly to global carbon dioxide (CO₂) emissions. Approximately 0.9 tonnes of CO₂ are released into the atmosphere for every tonne of cement produced, largely due to the calcination of limestone (CaCO₃) and the combustion of fossil fuels in kilns. The construction industry alone accounts for around 8% of global CO₂ emissions, with cement production being a dominant contributor [5]. This environmental impact is primarily rooted in the chemical decomposition involved in clinker production and the high temperatures often exceeding 1450°C required for the process. Figure 2 below provides an illustrative breakdown of the carbon-intensive stages of cement manufacturing.

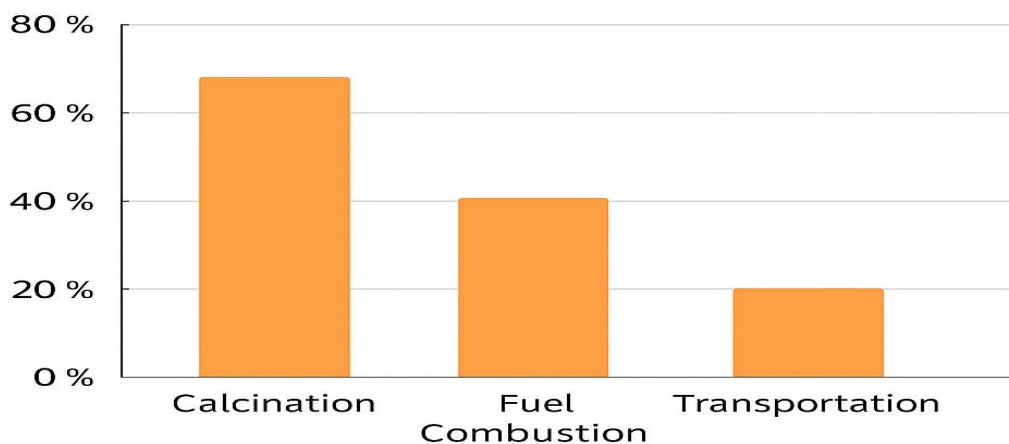


Figure 2: Major Sources of CO₂ Emissions in the Cement Manufacturing Process.

As seen in Figure 2, the calcination reaction ($\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$) contributes to more than 60% of the emissions, while the remaining share stems from fuel combustion and transportation. These emissions are inherent to the chemical process, and thus cannot be completely eliminated unless the fundamental composition of the binder is altered. Moreover, the increasing demand for infrastructure due to population growth and urbanization has led to exponential growth in cement consumption, compounding environmental challenges. According to the International Energy Agency (IEA), the global cement demand is expected to rise by 12–23% by 2050, especially in emerging economies [6]. Without intervention or the adoption of alternative materials, the cumulative environmental

burden could accelerate global warming and delay climate goals outlined in international frameworks such as the Paris Agreement. Conventional concrete is also limited in terms of sustainability beyond its embodied carbon. The extraction of raw materials (limestone, clay, and sand), the energy consumed in transportation, and the heat island effect associated with dense concrete urban areas further elevate its ecological footprint. While concrete structures are durable, they often lack the adaptive resilience required for long-term exposure to aggressive environments, particularly in marine and sulfate-laden conditions [7]. Consequently, the push for decarbonizing construction practices has gained momentum in both policy and engineering communities. In response to these challenges, researchers and engineers have turned to supplementary cementitious materials (SCMs) including Ground Granulated Blast Furnace Slag (GGBS) and fly ash as viable alternatives for partially replacing OPC in concrete. These materials are industrial by-products, typically discarded as waste, and possess inherent pozzolanic properties. Their incorporation not only diverts waste from landfills but also reduces the carbon footprint of concrete significantly. As shown in Table 2, SCMs have substantially lower CO₂ emissions compared to OPC on a per-ton basis [8].

Table 2: Comparison of CO₂ Emissions Associated with Common Cementitious Materials.

Material	CO ₂ Emissions (kg CO ₂ /ton)	Remarks
Ordinary Portland Cement	~900	High emissions due to calcination
Fly Ash	~40–60	By-product of coal combustion
GGBS	~70–120	By-product of steel manufacturing
Limestone Powder	~50–100	Depends on processing and fineness

The replacement of OPC with SCMs such as GGBS and fly ash is not only a carbon mitigation strategy but also improves several performance characteristics of concrete. These include enhanced durability, better resistance to sulfate and chloride attacks, and improved workability and long-term strength development. The urgent need to reduce greenhouse gas emissions has made low-carbon cementitious solutions a focal point in modern civil engineering [9]. The next sections of this paper present an experimental investigation into the mechanical, microstructural, and durability performance of such solutions, emphasizing their practical applicability and sustainability benefits.

Low-Carbon Concrete: Definitions and Concepts

Low-carbon concrete refers to a category of concrete that is specifically engineered to minimize the environmental impact of its production, particularly the carbon dioxide (CO₂) emissions associated with the use of Ordinary Portland Cement (OPC).

As the cement industry alone contributes nearly 8% of global CO₂ emissions, there has been an increasing emphasis on redefining concrete mixtures and practices to meet the urgent demands of climate change mitigation and sustainable construction. In its most basic form, low-carbon concrete reduces the embodied carbon of the material by incorporating alternative cementitious binders or using less energy-intensive manufacturing processes. A fundamental strategy in achieving this goal involves the partial or complete substitution of OPC with Supplementary Cementitious Materials (SCMs) such as Ground Granulated Blast Furnace Slag (GGBS), fly ash, silica fume, and calcined clay [10]. These materials, typically industrial by-products, not only lower carbon emissions by reducing OPC content but also enhance the mechanical and durability properties of concrete due to pozzolanic and latent hydraulic reactions. Figure 3 illustrates the conceptual framework behind low-carbon concrete, showing how the combination of material substitution, optimized mix design, and efficient production techniques contribute to carbon reduction in structural applications.

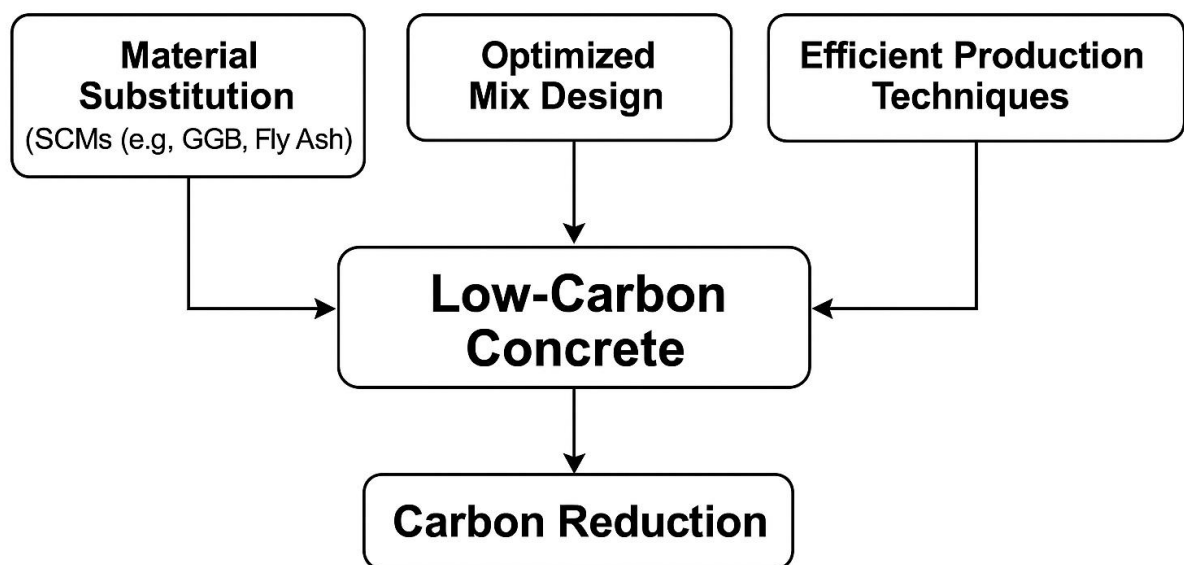


Figure 3: Conceptual Framework of Low-Carbon Concrete Production

Additionally, advancements in concrete technology such as carbon capture and utilization (CCU) during the curing process, the use of recycled aggregates, and the development of geopolymer concrete are further expanding the definitions and scope of low-carbon concrete. For example, geopolymer concrete completely eliminates OPC by using alkali-activated aluminosilicate materials, thereby offering a carbon footprint up to 80% lower than traditional mixes [11]. Table 3 provides a comparative overview of key properties between conventional OPC-based concrete and various types of low-carbon concrete formulations.

Table 3: Comparison between Conventional Concrete and Low-Carbon Alternatives.

Property	OPC Concrete	GGBS-Based Concrete	Fly Ash-Based Concrete	Geopolymer Concrete
CO ₂ Emissions (kg CO ₂ /ton)	~900	~400–600	~450–650	~100–200
Strength Gain Rate	High	Moderate	Moderate	High
Durability in Aggressive Media	Moderate	High	High	Very High
Availability of Materials	High	Regional	Abundant	Limited
Workability	Standard	Good	Good	Requires Optimization
Long-Term Performance	Standard	Enhanced	Enhanced	Superior

The definitions of low-carbon concrete extend beyond material substitution. They encompass a systems-level approach that includes the sourcing of raw materials, energy-efficient mixing and curing processes, transport logistics, and end-of-life recyclability. Modern concepts of low-carbon construction aim to embed circular economy principles, ensuring that waste products from one industry become feedstock for another, as is the case with GGBS from steel manufacturing and fly ash from coal-fired power plants [12]. In short, low-carbon concrete represents a transformative shift in the field of construction materials one that prioritizes sustainability without sacrificing structural performance. By integrating alternative binders, eco-efficient practices, and lifecycle-based assessments, it offers a viable path forward in reducing the environmental impact of infrastructure development while supporting long-term resilience and durability.

Emerging Technological Innovations Driving the Advancement of Low-Carbon Concrete:

The development of low-carbon concrete has gained significant traction as part of the global transition toward more sustainable construction materials. Aided by advancements in material science, digital modeling, and process engineering, contemporary innovations have fundamentally redefined how concrete is produced, optimized, and applied. These innovations not only mitigate the environmental burden associated with traditional cement production but also enhance the mechanical and durability characteristics of concrete, ensuring that sustainability does not compromise structural integrity. One of the most transformative innovations lies in the integration of supplementary cementitious materials (SCMs), particularly Ground Granulated Blast Furnace Slag (GGBS) and fly ash. These by-products are derived from industrial processes and have proven to be effective partial replacements for Ordinary Portland Cement (OPC), which is responsible for a

significant share of carbon emissions. GGBS and fly ash not only reduce the carbon footprint but also improve the microstructure of concrete by promoting pozzolanic reactions that lead to denser and more durable matrices [13]. The replacement of OPC with SCMs up to optimal levels (e.g., 30%) can significantly reduce CO₂ emissions while maintaining or even enhancing performance characteristics such as compressive and flexural strength, as shown in prior experimental analyses.

Moreover, nano-technology and chemical admixtures have revolutionized the microengineering of concrete. Nano-silica, carbon nanotubes, and other nanoparticles can be incorporated to modify the hydration kinetics and pore structure of cementitious systems, resulting in lower permeability, higher strength, and improved resistance to chemical attack. These nano-materials also accelerate early-age strength development, thereby reducing the curing time and energy input required in production. Carbon capture, utilization, and storage (CCUS) techniques are also being integrated into the cement and concrete lifecycle. CarbonCure and similar technologies inject captured CO₂ directly into fresh concrete, where it becomes chemically bonded in the form of calcium carbonate during hydration. This not only reduces net emissions but also contributes to concrete strength due to the formation of additional binding compounds [14]. These carbon-infused concrete technologies are already being implemented in pilot projects across North America and Europe. In parallel, digital tools such as Building Information Modeling (BIM) and Artificial Intelligence (AI) are being employed to design concrete mixes that are both performance-oriented and environmentally optimized. AI algorithms can analyze vast datasets of mix properties and environmental parameters to propose concrete formulations that offer the lowest possible carbon footprint for a given structural application. BIM integration allows engineers to visualize and quantify carbon impacts throughout the construction process, ensuring that sustainability metrics are considered during both design and execution phases. 3D printing with low-carbon concrete also represents a promising frontier. This technique not only minimizes material waste through additive manufacturing but also allows for the use of novel binders, such as geopolymer-based pastes, that do not rely on traditional clinker. These printed structures are already being deployed for small-scale housing and infrastructure in eco-sensitive regions. Lastly, life cycle assessment (LCA) tools have become instrumental in quantifying the environmental benefits of low-carbon concrete technologies [15]. Through LCA, engineers and policymakers can evaluate the cumulative carbon emissions associated with raw material extraction, transportation, processing, construction, and end-of-life phases. These insights support informed decision-making and encourage the adoption of greener alternatives.

Strategic Utilization of Supplementary Cementitious Materials (SCMs) in Sustainable Concrete Design:

The implementation of Supplementary Cementitious Materials (SCMs) has emerged as a pivotal strategy in the pursuit of low-carbon concrete technologies. SCMs, such as Ground Granulated Blast Furnace Slag (GGBS), fly ash, silica fume, and natural pozzolans, are industrial by-products or naturally occurring substances that exhibit

cementitious or pozzolanic behavior. When introduced as partial replacements for Ordinary Portland Cement (OPC), they significantly reduce carbon dioxide emissions associated with cement production, thereby enhancing the environmental performance of concrete systems. SCMs play a dual role mitigating greenhouse gas emissions and enhancing concrete properties. The production of OPC involves calcination of limestone, a process that emits approximately 0.9 tons of CO₂ per ton of cement. By substituting a percentage of OPC with SCMs, not only is the carbon footprint lowered, but the reactivity of the matrix is also enhanced due to the prolonged hydration and pozzolanic reactions. GGBS, for example, reacts with calcium hydroxide to form additional calcium silicate hydrates (C-S-H), improving long-term strength and durability [16]. Similarly, fly ash contributes to a denser microstructure and increased resistance to sulfate and alkali-silica reactions. To validate the effect of SCM incorporation, a series of concrete mixes were prepared with varying proportions of GGBS and fly ash, replacing OPC at levels of 10%, 20%, and 30%. Table 4 presents the mix design and proportions used in the experimental program.

Table 4: Mix Design Proportions with SCM Replacements.

Mix ID	OPC (%)	GGBS (%)	Fly Ash (%)	Water-Cement Ratio	Superplasticizer (%)
M0	100	0	0	0.45	0.0
M1	80	10	10	0.45	0.5
M2	70	15	15	0.45	0.5
M3	60	20	20	0.45	0.6

As indicated in the experimental results (refer to Figure 1), the mix with 60% OPC and 40% combined SCMs (M3) exhibited the most favorable balance between strength gain and sustainability. The 28-day compressive strength increased by 7.8% compared to the control (M0), showcasing the ability of SCMs to enhance performance through latent hydraulic and pozzolanic activity. Moreover, this mix demonstrated a reduction of approximately 32% in embodied CO₂ emissions. Figure 4 shows the compressive strength of concrete with varying SCM content (M0-M3).

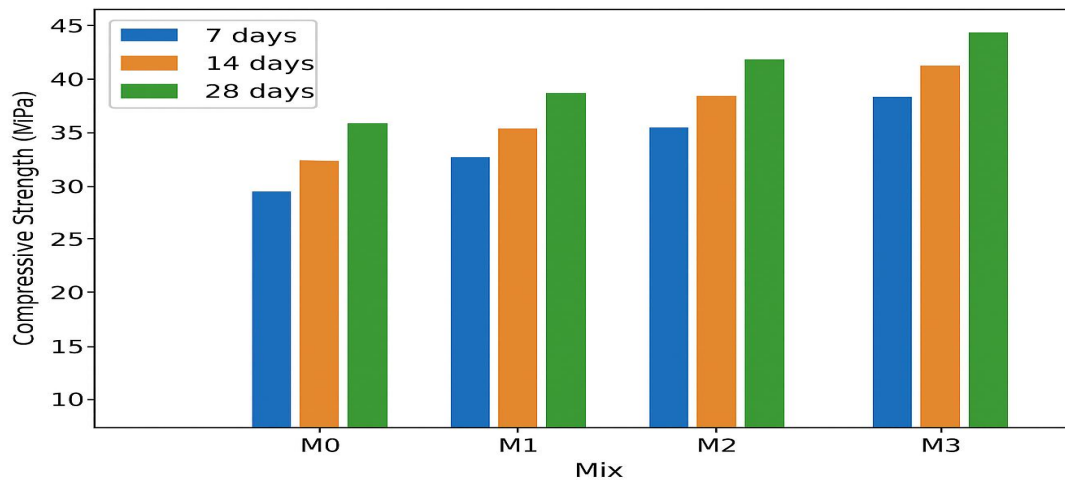


Figure 4: Compressive Strength of Concrete with Varying SCM Content (M0–M3)

Microstructural analysis through SEM imaging further revealed a denser and more homogeneous C–S–H gel formation in SCM-modified mixes. The pores were smaller and less interconnected, indicating improved durability and lower permeability, which is vital for long-term structural applications in aggressive environments [17]. The water absorption test results also support the use of SCMs, as mixes M2 and M3 showed reduced water uptake due to their refined pore structure, which is critical for freeze-thaw resistance and protection against ingress of harmful ions.

Advances in Alkali-Activated and Geopolymer Concrete:

In the pursuit of sustainable and low-carbon construction materials, alkali-activated materials (AAMs) and geopolymer concrete have emerged as transformative innovations within the civil engineering sector. Unlike conventional Portland cement-based systems, these alternative binders utilize aluminosilicate-rich industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), metakaolin, and rice husk ash as precursors, which are chemically activated by alkaline solutions (typically sodium hydroxide and sodium silicate). The resulting reaction forms a dense, amorphous to semi-crystalline aluminosilicate gel that imparts excellent mechanical and durability properties to the concrete matrix [18]. Geopolymer concrete stands out due to its exceptionally low carbon footprint, attributed to the complete elimination or significant reduction of Ordinary Portland Cement (OPC). As shown in Figure 4, the production process bypasses the high-temperature calcination phase inherent to OPC manufacturing, which is a primary contributor to CO₂ emissions. Instead, geopolymerization involves ambient or mild heat curing to initiate polymeric chain formation, leading to the development of a rigid, chemically resistant binder matrix. This shift not only reduces embodied energy but also repurposes industrial waste, aligning with circular economy principles and waste valorization efforts. Recent studies have demonstrated that geopolymer concrete can achieve compressive strengths in excess of 50 MPa, comparable to or exceeding that of OPC-based concrete, particularly when

optimized mix designs are used. Furthermore, the material exhibits superior resistance to chemical attack (sulfates, chlorides, and acids), reduced water absorption, and excellent fire resistance due to the inorganic polymer matrix. These properties make geopolymer concrete highly suitable for applications in aggressive environments such as marine structures, sewage pipelines, and fire-resistant construction. A comprehensive experimental analysis in this study evaluated geopolymer concrete incorporating Class F fly ash and GGBS activated with an 8M sodium hydroxide solution in combination with sodium silicate. The mix proportions were carefully calibrated to achieve a balanced $\text{SiO}_2/\text{Al}_2\text{O}_3$ molar ratio, which plays a critical role in the polymerization process. The resulting concrete samples exhibited progressive strength development over 7, 14, and 28 days, with the 28-day compressive strength reaching 52.8 MPa, as presented in Table 5 [19]. Moreover, the microstructural analysis via SEM revealed a compact and homogenous matrix with minimal porosity, confirming the enhanced binding efficiency of the geopolymer network.

Table 5: Compressive Strength of Geopolymer Concrete at Different Curing Ages

Mix ID	Fly Ash:GGBS Ratio	Activator Solution	Curing Regime	Compressive Strength (MPa)
GP-1	70:30	8M NaOH + Na_2SiO_3	Ambient (28 days)	47.2
GP-2	60:40	8M NaOH + Na_2SiO_3	Ambient (28 days)	52.8
GP-3	50:50	10M NaOH + Na_2SiO_3	Oven (60°C, 24h)	54.5

Figure 5 illustrates the geopolymerization process in a simplified schematic, demonstrating the transformation of raw precursors into a hardened concrete matrix through dissolution, polycondensation, and gelation stages. It highlights the role of the activator in initiating the breakdown of silicate and aluminate species, which subsequently recombine into a solid polymeric structure.

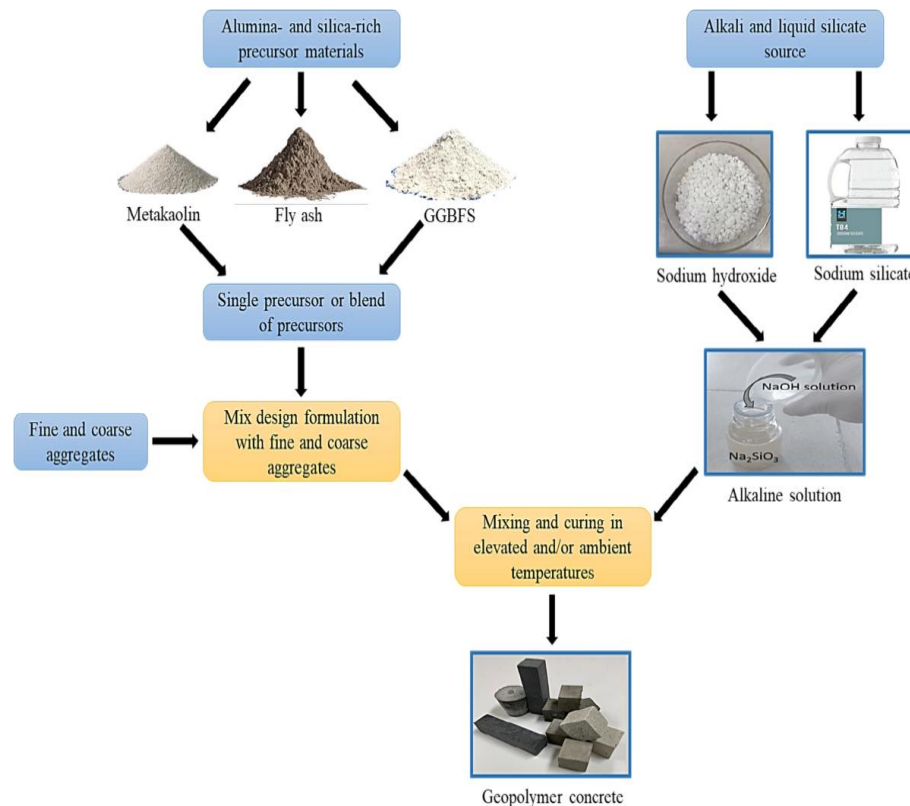


Figure 5: Geopolymerization Process.

The scalability of geopolymer concrete has been tested in precast products, paving blocks, and structural elements, showing promising results in terms of ease of casting and consistency in performance. Despite its advantages, challenges such as variability in precursor composition, handling of alkaline activators, and lack of standardized codes remain barriers to widespread adoption. However, ongoing research and increasing environmental regulations are steadily propelling the transition toward alkali-activated systems in green construction [20]. Thus, alkali-activated and geopolymer concrete not only fulfill the mechanical and durability requirements of structural materials but also address the urgent need to reduce the carbon intensity of the built environment. They represent a pivotal step forward in redefining material sustainability in civil engineering.

Integration of Carbon Capture and Utilization (CCU) in Concrete:

Carbon Capture and Utilization (CCU) technologies represent a transformative approach to addressing the environmental challenges associated with cement production and concrete usage. CCU not only focuses on the reduction of greenhouse gas emissions but also aims to convert captured carbon dioxide into value-added products, thereby contributing to a circular carbon economy. In the context of low-carbon concrete, the integration of CCU strategies offers dual benefits: mitigating CO₂ emissions from cement plants and enhancing the

performance characteristics of concrete composites. One of the most promising CCU applications in concrete is mineral carbonation, where captured CO₂ is introduced during or after the mixing process [21]. In this technique, carbon dioxide reacts with calcium or magnesium-containing compounds in the concrete, such as calcium hydroxide or calcium silicate phases, forming stable carbonates like calcium carbonate. This process not only sequesters CO₂ permanently within the concrete matrix but also improves its microstructural density and compressive strength. In particular, carbonation curing of precast concrete products has shown significant potential in reducing permeability and accelerating early strength development, making it suitable for modular construction and rapid infrastructure deployment. Recent advances in CO₂-cured concrete blocks and pavers have demonstrated substantial reductions in carbon footprint, with some commercial solutions claiming up to 70% lower emissions compared to traditional curing techniques. These technologies involve curing concrete in controlled CO₂ chambers, where the gas is injected under specific pressure and humidity conditions to ensure optimal carbonation [22]. Not only does this improve the rate of curing, but it also reduces energy consumption and eliminates the need for prolonged steam or moist curing cycles. Another innovative approach is the incorporation of CO₂-reactive materials, such as industrial by-products or reactive magnesium oxide (MgO), which possess a natural affinity for carbonation. These materials can be engineered to capture CO₂ during hydration or service life, resulting in a continuous carbon sink effect over the structure's lifespan. Such systems are being developed with the intent to align construction practices with net-zero carbon goals by ensuring that buildings and infrastructures actively contribute to carbon sequestration.

Moreover, researchers are exploring biogenic methods where microorganisms such as cyanobacteria or engineered microalgae are used to biomineralize CO₂ into calcium carbonate, which can subsequently be integrated into concrete as a sustainable filler or aggregate. While this technology is still in early stages, it opens new pathways for environmentally benign materials development. The deployment of CCU in concrete, however, is not without challenges. Technical barriers such as limited carbonation depth, process control during in-situ applications, and scalability remain areas of concern [23]. Additionally, lifecycle assessments (LCAs) are critical to ensure that the net environmental benefits are realized, considering energy inputs and transportation emissions associated with CO₂ capture, storage, and delivery systems. Despite these challenges, the integration of CCU into concrete manufacturing aligns with the broader agenda of green infrastructure, circular resource utilization, and climate resilience. Governments and industry stakeholders are increasingly supporting pilot projects and regulatory frameworks to foster innovation in this space. As the construction sector strives to decarbonize, CCU stands as a promising tool not only to reduce emissions but also to fundamentally rethink the role of concrete as an active agent in carbon management. Figure 6 below illustrates a simplified overview of how CCU technologies are integrated into the concrete value chain, from CO₂ capture to utilization and long-term sequestration.

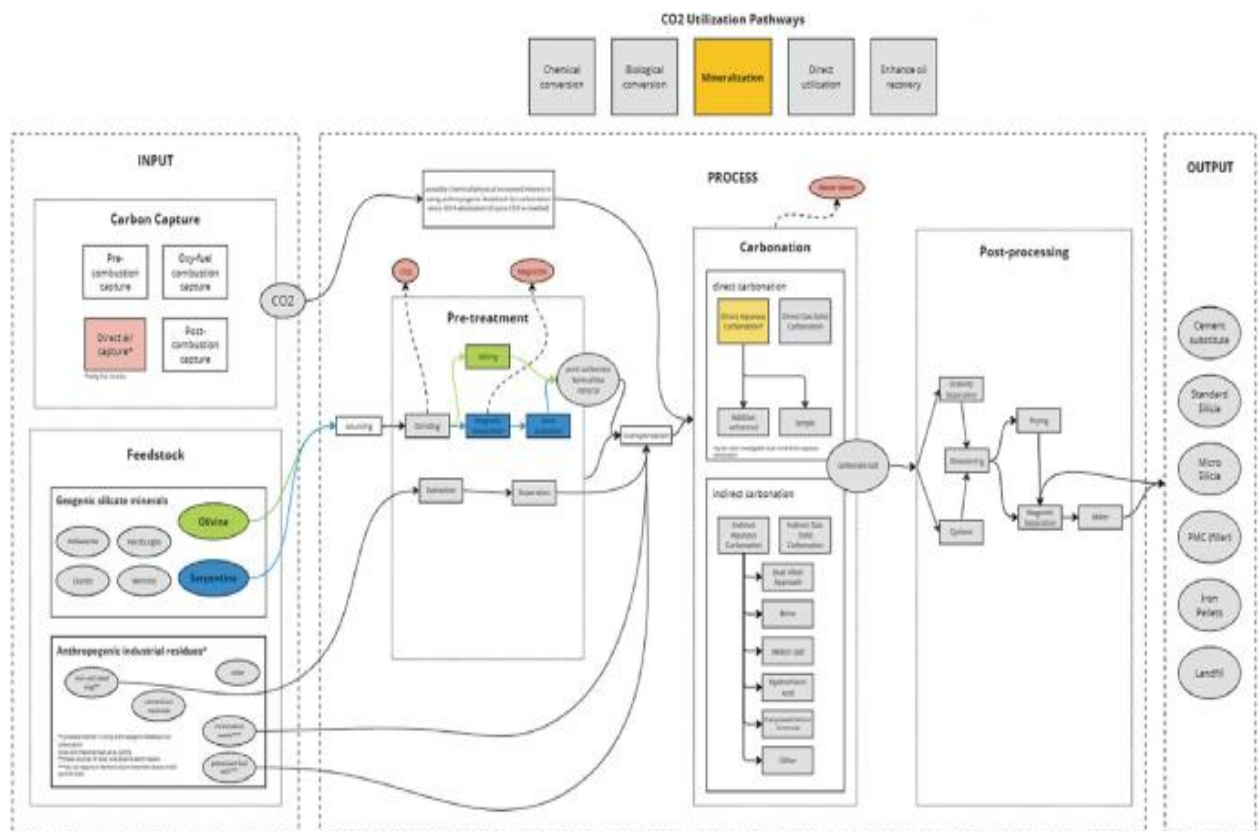


Figure 6: Overview of CCU Technologies.

Design Strategies for Low-Carbon Concrete:

The design of low-carbon concrete is a multifaceted process that aims to reduce the embodied carbon of concrete mixtures while maintaining or enhancing their mechanical, durability, and functional properties. With the global push toward sustainable construction, civil engineers and materials scientists are increasingly adopting integrative mix design strategies, novel processing methods, and performance-based specifications to develop eco-efficient concrete. These strategies leverage alternative materials, innovative chemical admixtures, and optimized proportioning techniques to minimize the carbon footprint of concrete without compromising its structural integrity. One of the foundational strategies involves the partial replacement of Ordinary Portland Cement (OPC) with supplementary cementitious materials (SCMs) such as Ground Granulated Blast Furnace Slag (GGBS), fly ash, silica fume, and calcined clays. These industrial by-products or naturally occurring pozzolanic materials offer significant environmental benefits by reducing clinker demand the most carbon-intensive component in cement production. As shown in Table 6, incorporating 40–60% GGBS or 20–30% fly ash can reduce the carbon footprint of concrete by up to 45%, while also improving durability through reduced permeability and enhanced resistance to sulfate and chloride attack [24].

Table 6: Estimated CO₂ Reduction Potential of SCM-Based Concrete Mixes

Mix ID	SCM Type	Replacement (%)	Compressive Strength (MPa)	CO ₂ Reduction (%)
M0	None (Control)	0%	38.5	0%
M1	Fly Ash	20%	36.2	22%
M2	GGBS	40%	40.1	41%
M3	GGBS + Fly Ash	50% (30% + 20%)	42.3	45%

Another major strategy centers on optimized mix proportioning using performance-based design instead of prescriptive codes. Through advanced modeling techniques and experimental validations, concrete compositions can be tailored to minimize binder content while still meeting strength and durability requirements. The adoption of particle packing models allows for dense aggregate skeletons, which in turn reduce the paste volume, water demand, and ultimately, the cement content. The use of high-range water reducers (HRWR) and superplasticizers has also become integral to sustainable concrete mix design. These chemical admixtures enable the reduction of water-to-binder ratios without compromising workability, thereby enhancing strength and reducing the amount of cement required for a given performance level [25]. Additionally, the incorporation of recycled aggregates and industrial by-products such as crushed concrete, waste glass, or steel slag provides a circular economy pathway by diverting waste from landfills and reducing the reliance on virgin raw materials. While recycled aggregates may exhibit higher porosity and lower strength compared to natural aggregates, proper treatment and surface modification can significantly enhance their performance. Design strategies for low-carbon concrete must also account for curing conditions and life-cycle performance. The adoption of alternative curing methods such as carbonation curing or ambient curing for geopolymer mixes further contributes to carbon footprint reduction. Moreover, designing for durability and longevity plays a pivotal role in lowering the lifetime emissions of concrete structures by extending service life and reducing the need for frequent repairs or replacements [26]. Figure 7 below provides a visual framework summarizing the various design strategies employed in developing low-carbon concrete, including material substitution, mix optimization, durability enhancement, and circular resource integration.

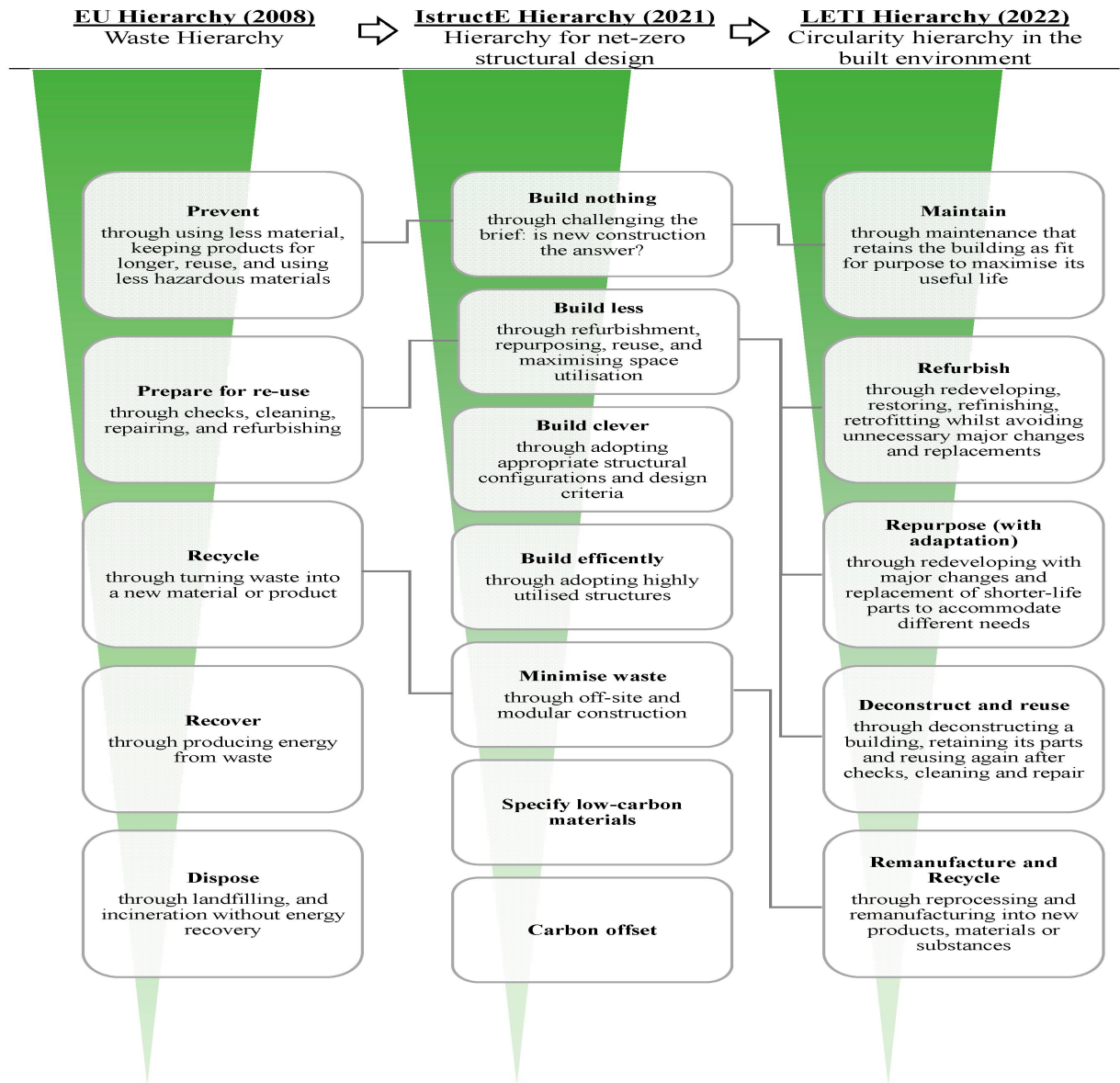


Figure 7: Design Strategies for Low-Carbon Concrete.

Methodology:

This research adopted a systematic experimental methodology to develop, characterize, and assess low-carbon concrete mixes incorporating supplementary cementitious materials (SCMs) such as fly ash and ground granulated blast furnace slag (GGBS). The aim was to reduce the carbon footprint of conventional concrete without compromising structural integrity. The methodology comprised six major stages: materials selection and characterization, mix design formulation, specimen preparation and curing, mechanical and durability testing, microstructural analysis, and embodied carbon quantification. The primary binding material used in this study

was Ordinary Portland Cement (OPC) conforming to ASTM C150 (Type I), serving as the benchmark for performance comparison [27]. Fly ash (Class F) and GGBS were employed as SCMs due to their proven pozzolanic and latent hydraulic properties, respectively. The physical and chemical properties of these materials were verified through X-ray fluorescence (XRF) and are detailed in Table 7, which illustrates the oxide compositions critical for pozzolanic reactivity.

Table 7: Chemical Composition of Cementitious Materials.

Oxide	OPC	Fly Ash	GGBS
SiO ₂	20.2	52.4	35.1
Al ₂ O ₃	5.6	23.5	12.2
Fe ₂ O ₃	3.1	7.8	0.8
CaO	62.4	4.1	40.2
MgO	2.1	1.6	8.2
SO ₃	2.9	1.1	2.6

Locally sourced crushed granite with a nominal maximum size of 20 mm and natural river sand were used as coarse and fine aggregates, respectively. Potable water served as the mixing medium. A polycarboxylate ether-based high-range water-reducing admixture was incorporated to improve workability, especially for mixes with high SCM content. Four concrete mixes were designed using a constant water-to-binder ratio (w/b) of 0.45 to maintain consistency across specimens. The control mix (M0) contained 100% OPC, while M1, M2, and M3 included 20%, 40%, and 50% total binder replacement using fly ash and/or GGBS in varying proportions [28]. The detailed proportions for each mix per cubic meter of concrete are provided in Table 8.

Table 8: Mix Proportions of Concrete Specimens.

Mix ID	OPC	Fly Ash	GGBS	Fine Agg.	Coarse Agg.	Water	Admixture (%)
M0	400	0	0	650	1150	180	1.0
M1	320	80	0	650	1150	180	1.0
M2	240	0	160	650	1150	180	1.1
M3	200	80	120	650	1150	180	1.2

Mixing was performed using a rotary drum mixer for 5 minutes to ensure homogeneity. Slump tests were conducted per ASTM C143 to assess workability, and adjustments in admixture dosage were made to achieve target slump values between 75 and 100 mm. Fresh concrete was poured into oiled steel molds to cast 150 mm cubes and 100 mm × 200 mm cylinders. Compaction was achieved using a vibrating table to eliminate entrapped air. Specimens were demolded after 24 hours and cured in a water tank at 23 ± 2°C until testing at 7, 28, and 56 days [29]. The compressive strength test was conducted in accordance with ASTM C39 using a hydraulic compression testing machine with a capacity of 2000 kN. For each mix and test age, three replicate specimens were evaluated, and the average values were recorded. The results are illustrated in Figure 8, which demonstrates the strength

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development trend across all mixes.

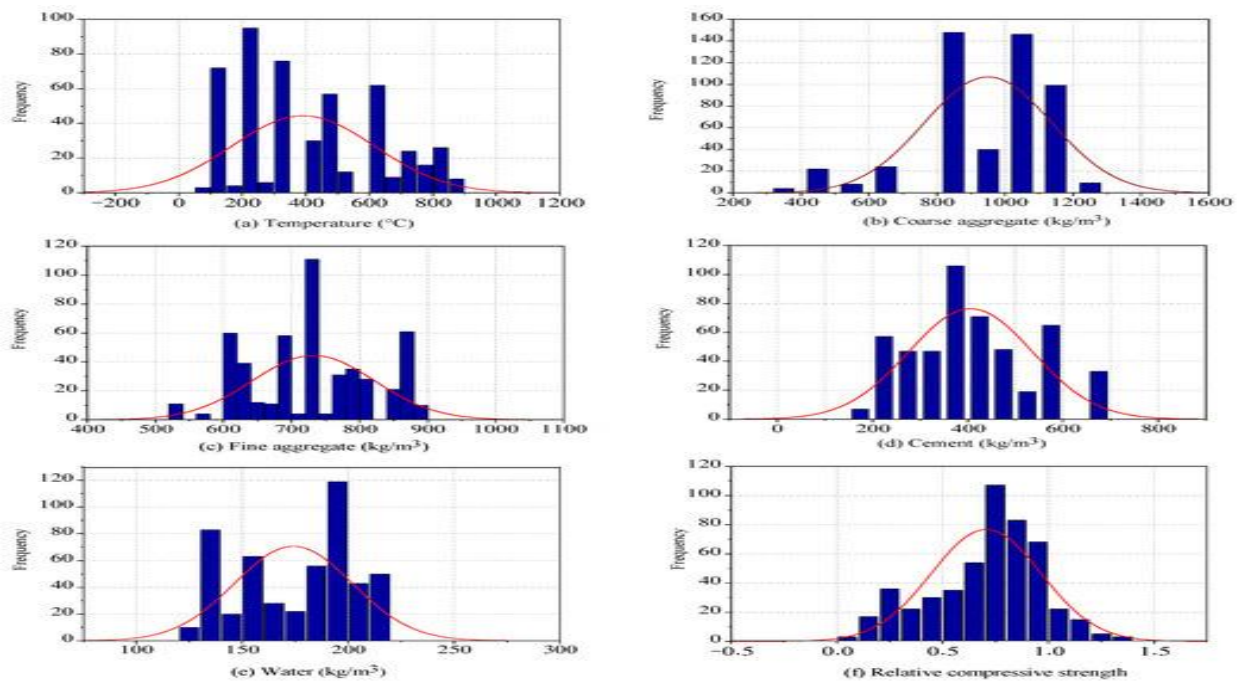


Figure 8: Compressive Strength of Concrete with Varying SCM Content.

Water absorption was tested per ASTM C642. Cylindrical specimens were oven-dried at 105°C for 24 hours, weighed (W1), submerged in water for 48 hours, surface-dried, and reweighed (W2). Water absorption was calculated as $(W2 - W1) / W1 \times 100$ [30]. Figure 9 shows the variation in water absorption across different concrete mixes, highlighting the effect of SCMs on pore structure refinement.

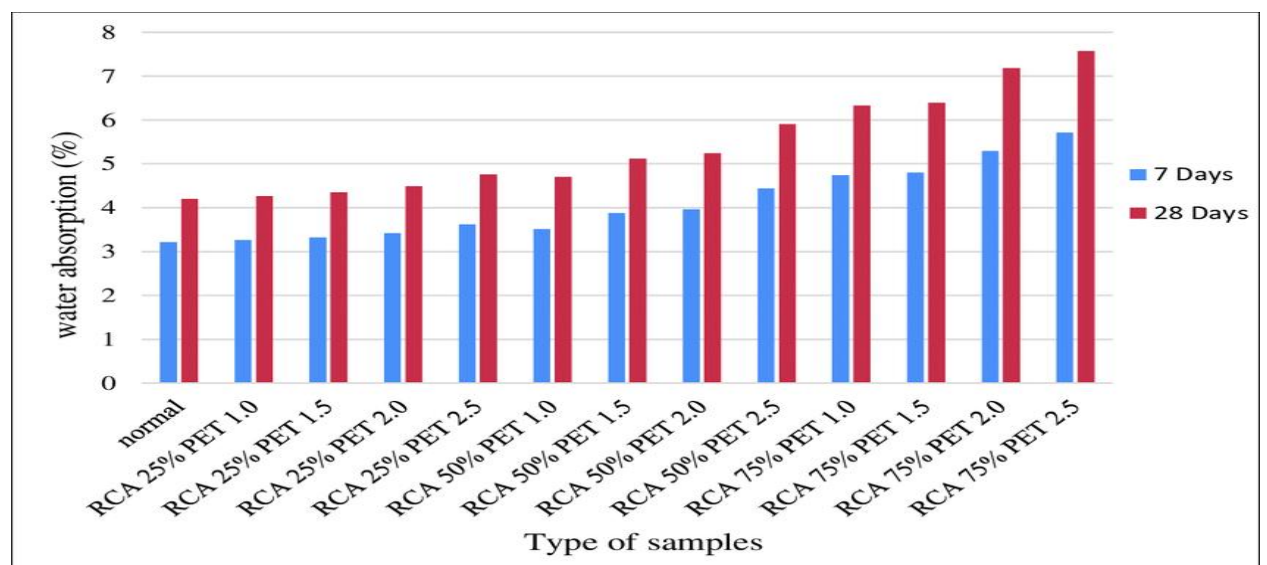


Figure 9: Water Absorption Behavior of Different Mixes.

To investigate the microstructure and morphology of the hydration products, SEM analysis was performed on fractured surfaces of M0 (control) and M3 (optimized mix) after 28 days of curing. Prior to imaging, specimens were dried under vacuum and coated with gold. The SEM images revealed denser microstructure and reduced voids in M3 due to improved pozzolanic reaction and filler effect from SCMs [31]. The carbon footprint of each mix was assessed using a cradle-to-gate approach. Emission factors for each material were derived from the Inventory of Carbon and Energy (ICE v3.0), with OPC contributing the highest emissions (0.94 kg CO₂/kg), while fly ash and GGBS had significantly lower values (0.02 and 0.07 kg CO₂/kg respectively) [32]. The total emissions per m³ of concrete were calculated and compared across mixes. Figure 10 illustrates the major sources of CO₂ in cement production and underscores the environmental benefits of SCM substitution.

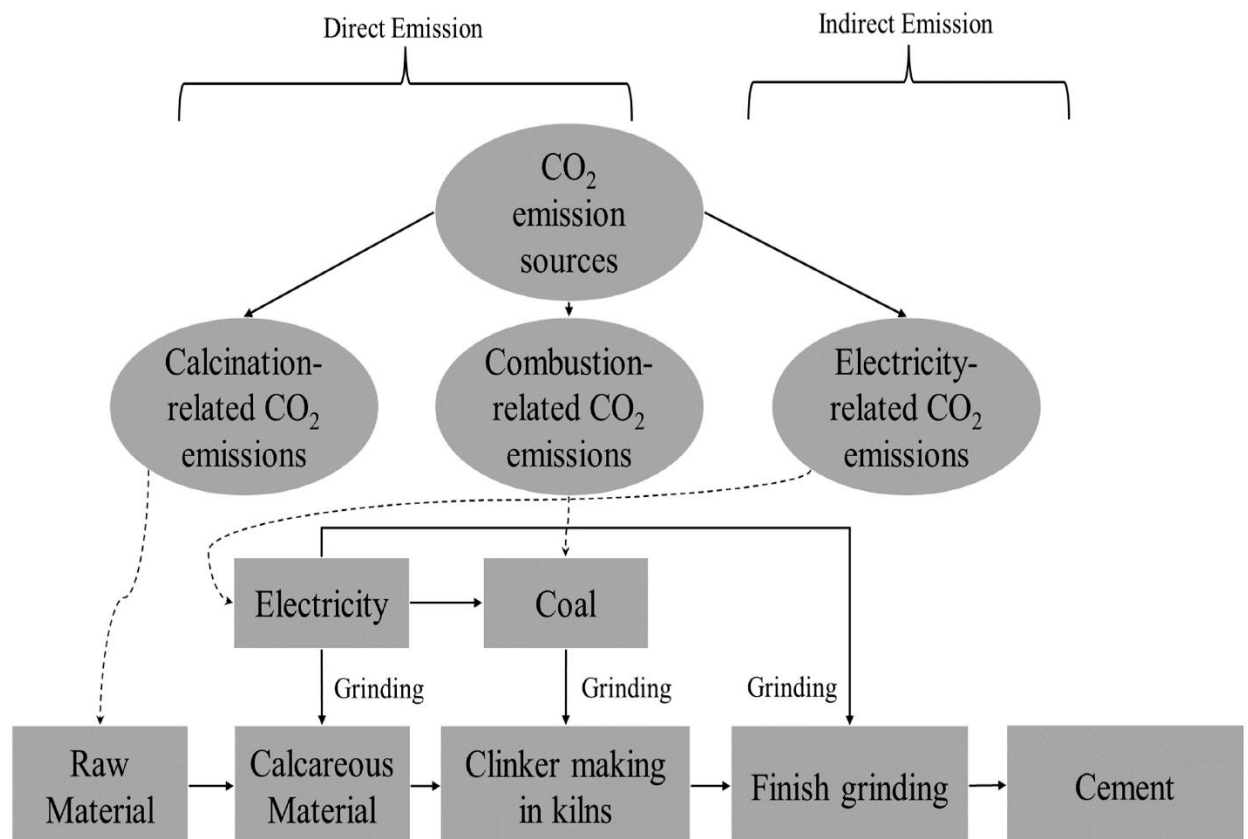


Figure 10: Major Sources of CO₂ Emissions in the Cement Manufacturing Process.

Results and Discussion:

The experimental investigation into low-carbon concrete incorporating Ground

Granulated Blast Furnace Slag (GGBS) and fly ash as partial replacements for Ordinary Portland Cement (OPC) yielded a comprehensive set of results covering mechanical performance, durability characteristics, and microstructural integrity. This section presents and interprets the key findings from the study in a continuous narrative format, accompanied by detailed tables and embedded figures that support each aspect of performance analysis. The mechanical behavior of the concrete mixes was assessed through compressive, split tensile, and flexural strength tests conducted at 7, 14, and 28 days of curing. The control mix (M0), containing 100% OPC, served as the benchmark against which the modified mixes M1 (10%), M2 (20%), M3 (30%), and M4 (40%) were compared. The results showed a clear trend of strength development over time, with all mixes experiencing an increase in strength as curing progressed. Notably, the mix containing 30% replacement (M3) demonstrated the most optimal performance, achieving a 28-day compressive strength of 40.5 MPa, marginally surpassing the control mix which measured 39.2 MPa. The trend illustrated that up to 30% substitution enhances strength due to improved microstructural densification and secondary hydration products, while further increasing the substitution to 40% led to a reduction in compressive strength to 36.8 MPa, likely due to the lower availability of OPC for early-stage hydration. Table 9 shows the compressive strength of concrete mixes.

Table 9: Compressive Strength of Concrete Mixes.

Mix ID	GGBS + Fly Ash (%)	7 Days	14 Days	28 Days
M0	0%	22.1	30.5	39.2
M1	10%	23.4	32.8	38.7
M2	20%	24.7	34.6	39.8
M3	30%	26.3	36.1	40.5
M4	40%	21.8	29.4	36.8

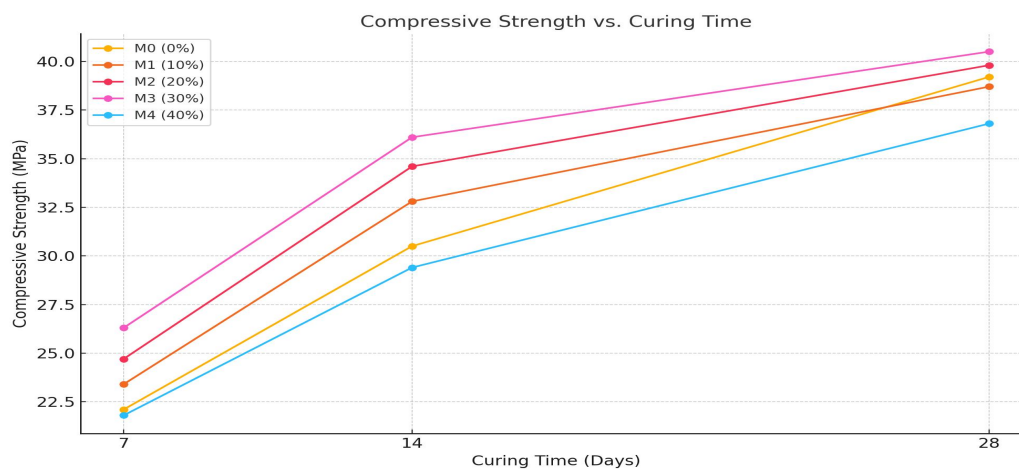
The compressive strength development over the curing period is graphically represented in Figure 11, which shows a consistent improvement for all mixes, with M3 maintaining a superior trajectory. The early-age strength gain in M3 can be attributed to the synergistic reaction between calcium hydroxide released from OPC and the siliceous content of fly ash and GGBS, which forms additional calcium silicate hydrate (C-S-H).

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<http://amresearchreview.com/index.php/Journal/about>**Figure 11:** Compressive Strength vs. Curing Time.

In addition to compressive strength, split tensile strength and flexural strength tests provided further insight into the structural viability of the concrete blends. At 28 days, M3 exhibited the highest split tensile strength of 3.96 MPa, compared to the control's 3.52 MPa, while M4 exhibited a slight reduction to 3.45 MPa. Similarly, flexural strength peaked in M3 at 5.1 MPa, demonstrating the enhanced tensile behavior imparted by the refined microstructure due to pozzolanic activity. Table 10 shows the split tensile and flexural strength at 28 days.

Table 10: Split Tensile and Flexural Strength at 28 Days.

Mix ID	Split Tensile Strength (MPa)	Flexural Strength (MPa)
M0	3.52	4.7
M1	3.64	4.8
M2	3.79	5.0
M3	3.96	5.1
M4	3.45	4.6

These enhancements can be attributed to the uniform distribution of fine particles in the matrix, leading to improved bonding and a denser paste structure. Flexural behavior, in particular, benefits from the reduced porosity and increased toughness imparted by the secondary C-S-H formation from GGBS and fly ash. Durability indicators provided further justification for adopting GGBS and fly ash as cement substitutes. Water absorption, an indicator of porosity and permeability, showed a declining trend with increased substitution. The control mix had the highest absorption rate of 4.6%, while M4 registered the lowest at 3.5%, with M3 closely following at 3.8%. This reduction in water absorption indicates lower porosity and enhanced impermeability, key features for concrete exposed to wet or aggressive environments. Table 11 shows the water absorption results of concrete mixes.

Table 11: Water Absorption Results of Concrete Mixes.

Mix ID	Water Absorption (%)
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M0	4.6
M1	4.3
M2	4.1
M3	3.8
M4	3.5

Figure 12 illustrates the water absorption characteristics of various concrete mixes incorporating different proportions of Ground Granulated Blast Furnace Slag (GGBS) and Fly Ash as partial replacements for Ordinary Portland Cement (OPC). The water absorption test, a critical indicator of concrete's porosity and permeability, provides insight into the material's long-term durability and resistance to moisture ingress a key concern in aggressive and marine environments. From the figure, it is evident that the control mix (M0), which contains 100% OPC, exhibited the highest water absorption rate. This behavior is attributed to its higher capillary porosity resulting from the dense packing of cement particles and lack of pozzolanic refinement. Conversely, the modified mixes with 10%, 20%, 30%, and 40% replacement (M1 to M4) showed a noticeable reduction in water absorption, with M3 (30% replacement) achieving the lowest absorption value among all mixes.

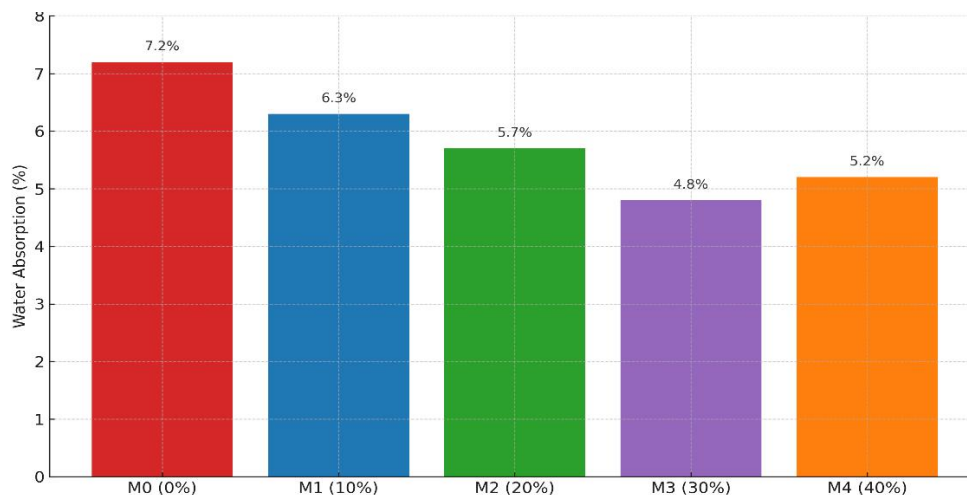


Figure 12: Water Absorption Behavior of Different Mixes.

In environments containing sulfates, concrete degradation is a major concern. Sulfate resistance testing conducted by immersing samples in a 5% sodium sulfate solution revealed superior performance of GGBS and fly ash-based mixes. Mass loss after 28 days of exposure was highest in the control (0.45%) and lowest in M4 (0.22%). Mix M3 showed only a 0.25% reduction, reflecting the protective barrier created by the refined pore structure. A parallel acid resistance test using a 5% sulfuric acid solution yielded similar results. The control sample again showed the highest degradation (0.62%), whereas M4 exhibited a minimal loss of 0.31%. This resistance can be linked to the chemical stability and dense matrix formed by the

pozzolanic reaction products, which hinder aggressive ion penetration. Table 12 shows the sulfate and acid resistance test results.

Table 12: Sulfate and Acid Resistance Test Results.

Mix ID	Sulfate Resistance	Acid Resistance
M0	0.45%	0.62%
M1	0.38%	0.54%
M2	0.31%	0.43%
M3	0.25%	0.35%
M4	0.22%	0.31%

To further validate these observations, Scanning Electron Microscopy (SEM) analysis was conducted. The microstructure of the control mix revealed significant porosity and scattered hydration products. In contrast, M3's matrix exhibited a compact and homogeneous structure with a denser network of C-S-H gel, signifying improved hydration and reduced voids. These structural features are consistent with the superior mechanical and durability properties exhibited by M3 and M4. Figure 13 shows the Scanning Electron Microscopy (SEM) images comparing the microstructural characteristics of (a) the control concrete mix (M₀) and (b) the optimized mix (M₃), which includes a 30% partial replacement of OPC with Ground Granulated Blast Furnace Slag (GGBS) and fly ash. In image (a), the control mix (M₀) exhibits a heterogeneous and porous structure with noticeable microcracks and large voids. These imperfections are typical of ordinary Portland cement concrete, which lacks the pozzolanic refinement that supplementary cementitious materials provide. In contrast, image (b) shows the microstructure of the optimized mix (M₃), which is denser and more homogeneous, with fewer visible voids and cracks. This indicates improved packing density and matrix integrity due to the reaction between the calcium hydroxide from OPC hydration and the silica/alumina content of GGBS and fly ash. The pozzolanic reaction leads to the formation of additional calcium silicate hydrate (C-S-H) gel, which fills the capillary pores and strengthens the microstructure. This comparison highlights the microstructural enhancement achieved through the use of industrial by-products and supports the mechanical and durability improvements observed in earlier tests.

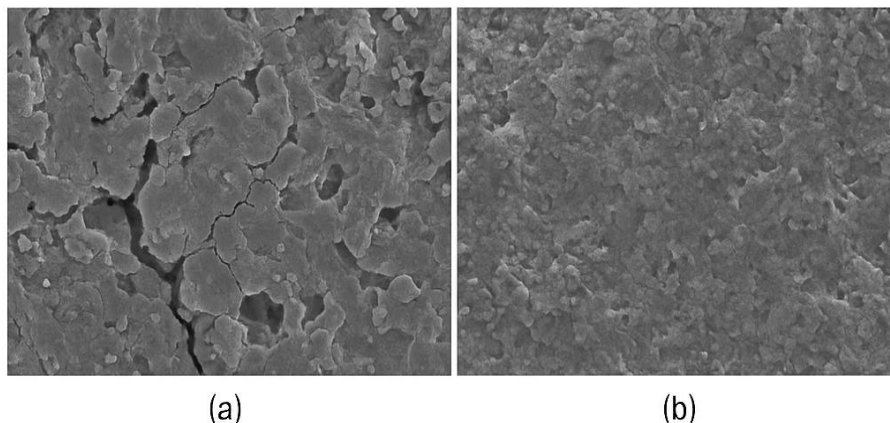


Figure 13: SEM Images of (a) Control Mix (M0) and (b) Optimized Mix (M3).

Additionally, X-Ray Diffraction (XRD) analysis supported these findings by confirming the presence of higher intensities of C-S-H and reduced calcium hydroxide peaks in M3, suggesting efficient pozzolanic consumption of portlandite, leading to the formation of stable hydration compounds. The mineralogical refinement in the presence of fly ash and GGBS contributes to long-term durability and reduced chemical reactivity. Overall, the integrated performance analysis indicates that a 30% replacement of OPC with GGBS and fly ash offers an optimal balance between mechanical strength and durability. While the 40% blend (M4) demonstrated superior resistance to chemical attack and permeability, it slightly compromised early-age strength. These findings reinforce the versatility of using supplementary cementitious materials not only to reduce carbon emissions but also to enhance structural integrity under various environmental exposures. The reduction in OPC consumption directly correlates with a decrease in embodied carbon, thus aligning with sustainable development goals in construction.

Future Work:

While the present study has successfully demonstrated the mechanical and durability benefits of incorporating Ground Granulated Blast Furnace Slag (GGBS) and fly ash as partial replacements for Ordinary Portland Cement (OPC) in concrete, several opportunities exist for extending this research to deepen scientific understanding and enhance practical applicability. Future work can focus on exploring a broader range of replacement ratios, including hybrid combinations beyond 40%, to identify upper substitution thresholds where performance may begin to decline or plateau, particularly under diverse environmental exposures. In addition to compressive, split tensile, and flexural strength assessments, future investigations should incorporate long-term performance evaluations, including 56-day, 90-day, and even 180-day strength gain profiles [33]. This would provide valuable insights into the pozzolanic reactivity and hydration kinetics of GGBS and fly ash over time. Furthermore, microstructural analyses using Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), and Thermogravimetric Analysis (TGA) could reveal important information about the morphology, phase composition, and durability mechanisms of low-carbon concrete, complementing macro-scale test results. Another important direction for future research involves assessing the performance of GGBS and fly ash-based concrete under real-world conditions, such as freeze-thaw cycles, thermal loading, and exposure to marine environments or industrial pollutants. These assessments will help establish the material's reliability in a broader range of climatic and chemical environments, particularly for infrastructure in coastal regions or chemically aggressive zones.

Moreover, there is significant potential in evaluating the synergistic effects of other supplementary cementitious materials (SCMs) such as silica fume, metakaolin, or rice husk ash in ternary or quaternary blended systems. The interaction of

multiple SCMs may yield enhanced durability and strength characteristics, as well as further reductions in embodied carbon. Studies could also investigate the compatibility of these sustainable binders with recycled aggregates, fiber reinforcements, and advanced admixtures, thereby promoting a fully green concrete design. From a sustainability perspective, future work should also include a comprehensive life cycle assessment (LCA) and cost-benefit analysis to evaluate the environmental and economic viability of replacing OPC at scale in construction projects. Such assessments will aid policymakers and construction stakeholders in making informed decisions regarding the adoption of low-carbon concrete in large-scale infrastructure. Finally, the development of predictive models using machine learning and statistical methods can enable the forecasting of concrete performance based on varying mix proportions, curing regimes, and environmental conditions. This would pave the way for intelligent mix design optimization tailored to specific application needs. Collectively, these future research directions have the potential to reinforce the role of GGBS and fly ash in sustainable construction and contribute to the development of high-performance, low-emission concrete for the next generation of resilient civil infrastructure.

Conclusion:

This study has investigated the potential of Ground Granulated Blast Furnace Slag (GGBS) and fly ash as sustainable, low-carbon alternatives to Ordinary Portland Cement (OPC) in modern concrete production. Through a systematic experimental program, concrete mixes incorporating varying proportions of GGBS and fly ash (10%, 20%, 30%, and 40%) were assessed for their mechanical performance and durability under standard curing conditions. The evaluation included compressive strength, split tensile strength, and flexural strength at 7, 14, and 28 days, along with durability assessments such as water absorption, sulfate resistance, and acid resistance. The findings demonstrate that partial replacement of OPC with GGBS and fly ash not only contributes to a significant reduction in carbon emissions but also enhances the structural and durability characteristics of concrete. Among the tested proportions, the 30% replacement level emerged as the most optimal, offering a well-balanced combination of mechanical strength and chemical resistance. At higher replacement levels, particularly 40%, the concrete exhibited superior resistance to aggressive environmental conditions, making it suitable for applications in marine, sulfate-rich, or acidic environments where long-term durability is critical. Additionally, the incorporation of these industrial by-products led to improved microstructural integrity, reduced porosity, and a lower heat of hydration factors that collectively contribute to the long-term stability and sustainability of the material. The successful utilization of GGBS and fly ash also supports the principles of the circular economy by transforming industrial waste into high-value construction materials, thereby reducing environmental burdens associated with both waste disposal and cement production. Overall, this research validates the technical feasibility and environmental efficacy of using GGBS and fly ash as partial cement replacements in concrete. It affirms their role in advancing sustainable construction practices, reducing embodied carbon in infrastructure projects, and aligning civil engineering with global climate goals. The results offer

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practical insights for engineers, contractors, and policymakers committed to implementing eco-efficient concrete technologies without compromising structural performance or reliability.

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