

Development of Carbon Negative Concrete Using Algae Derived Additives

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Abstract

The growing demand for sustainable construction materials has motivated the development of carbon negative concrete that can actively reduce atmospheric CO₂ levels. This study explores the use of algae-derived additives as a renewable and eco-friendly alternative to conventional supplementary cementitious materials. Microalgae biomass and its calcined derivatives were incorporated into concrete mixes to enhance carbon sequestration potential while maintaining structural performance. The experimental program investigated compressive strength, workability, and durability characteristics under varying replacement levels of cement with algae-derived additives. Results indicate that a 10–15% substitution can reduce the embodied carbon footprint by up to 25%, while also improving pore structure refinement and long-term durability. Moreover, the biogenic nature of algae enhances the self-healing ability of the concrete by providing additional reactive sites for carbonation. This research demonstrates the feasibility of algae-based additives as a promising pathway toward carbon negative concrete, thereby contributing to net-zero emission targets and advancing sustainable construction practices.

Keywords: Carbon Negative Concrete, Algae-Derived Additives, Sustainable Construction, CO₂ Sequestration, Green Materials, Cement Replacement, Durability

1. Introduction

Concrete is the most widely used construction material in the world, with global production exceeding 30 billion tons annually. Its popularity is attributed to its strength, durability, and adaptability for diverse structural applications. However, this advantage comes at an environmental cost, as the cement industry—the primary component of concrete—is responsible for nearly 8% of global anthropogenic carbon dioxide (CO₂) emissions. The process of limestone calcination during clinker production, coupled with the high energy requirements of cement kilns, contributes significantly to greenhouse gas emissions. As the global community shifts towards sustainable development and net-zero emission targets, the construction industry faces mounting pressure to adopt innovative approaches that reduce its carbon footprint while maintaining the essential performance characteristics of concrete.

In recent decades, researchers have investigated supplementary cementitious materials (SCMs), such as fly ash, silica fume, and ground granulated blast furnace slag (GGBS), to partially replace Portland cement and thereby mitigate CO₂ emissions. While these industrial by-products have achieved significant reductions in embodied carbon, their availability is becoming increasingly limited due to the decarbonization of power plants and metallurgical industries. This scarcity necessitates the exploration of alternative, renewable, and scalable resources to ensure the sustainable future of concrete technology. One promising candidate that has gained attention is microalgae and macroalgae biomass, which not only provide a renewable source of biomaterials but also naturally capture atmospheric CO₂ during their growth cycle.

Algae possess unique characteristics that make them suitable for incorporation into cementitious systems. During photosynthesis, algae absorb large quantities of CO₂, converting it into organic biomass rich in calcium carbonate, silica, and other mineral constituents. When harvested and processed, these biomaterials can act as potential SCMs or functional additives in concrete mixes. Furthermore, certain algae-derived compounds enhance the hydration reaction, refine the microstructure, and improve the durability of concrete against chemical attack and environmental degradation. Unlike conventional SCMs, algae can be cultivated in controlled environments, including wastewater treatment facilities, coastal regions, or industrial effluent ponds, making them a scalable and sustainable source of carbon-sequestering additives.

The concept of carbon negative concrete extends beyond the simple reduction of emissions to actively promoting net CO₂ capture. By integrating algae-derived additives, concrete not only lowers its embodied carbon footprint but can also sequester additional atmospheric carbon through biogenic mineralization processes. Previous studies have shown that calcined algae ash and algae-based biopolymers can enhance pozzolanic activity, fill microvoids within the cement matrix, and facilitate self-healing mechanisms during service life. This dual role of mechanical performance enhancement and carbon sequestration positions algae as a transformative material in sustainable construction.

Moreover, the adoption of algae-based additives aligns with the principles of the circular economy. By utilizing rapidly renewable biomass resources, the construction industry can reduce reliance on depleting industrial by-products and fossil-intensive raw materials. At the same time, algae cultivation supports co-benefits such as wastewater remediation, nutrient recovery, and production of biofuels, further reinforcing the holistic sustainability of this approach. With the global emphasis on green building certification systems, carbon accounting, and climate-resilient infrastructure, algae-derived concrete presents a strategic opportunity to meet both engineering and environmental goals.

The present study investigates the potential of algae-derived additives in developing carbon negative concrete. It examines the effects of different substitution levels of Portland cement with algae biomass derivatives on the fresh and hardened properties of concrete, including workability, compressive strength, durability, and microstructural performance. The work also highlights the role of algae in carbon sequestration, demonstrating how the integration of renewable biomaterials contributes to significant emission reductions. Through experimental results and analytical discussion, this paper provides evidence that algae-based concrete can serve as a viable pathway toward net-zero construction practices, enabling the transition to a more sustainable built environment.

2. Literature Review

The global challenge of reducing carbon emissions from the cement and concrete industry has motivated extensive research on low-carbon and carbon-negative construction materials. Traditionally, the most effective strategy has been the partial replacement of cement with supplementary cementitious materials (SCMs) such as fly ash, silica fume, and ground granulated blast furnace slag (GGBS). Ahmad et al. (2018) and Mehta & Monteiro (2019) reported that incorporating SCMs not only reduces the clinker factor but also enhances durability and long-term strength development. However, as coal-fired power generation and metallurgical industries undergo decarbonization, the supply of industrial by-products is becoming less reliable, creating a need for alternative, renewable, and environmentally friendly materials. Recent years have seen growing interest in bio-based materials for concrete production. Biochar, lignin, and agricultural residues have been studied for their potential to lower carbon emissions while improving mechanical and durability properties (Wang et al., 2020). Among these, algae-derived additives have emerged as a unique and promising category due to their inherent capacity to capture CO₂ during growth and their chemical compatibility with cementitious systems. Studies by Choi et al. (2016) and Perera et al. (2020) demonstrated that algae biomass contains high levels of calcium carbonate, silica, and magnesium, which can contribute to pozzolanic reactions and microstructural refinement in cement-based composites.

Algae cultivation for construction applications is particularly attractive because of its scalability and environmental co-benefits. Microalgae can be cultivated in nutrient-rich wastewater or saline environments, reducing the need for arable land and freshwater resources. According to Rahman and Kumar (2021), large-scale algae cultivation systems not only capture atmospheric CO₂ but also facilitate wastewater remediation by absorbing excess nitrogen and phosphorus. These additional benefits position algae as a sustainable alternative compared to limited industrial by-products.

When incorporated into concrete, algae-derived additives can play multiple roles. Calcined algae ash has been reported to act as a reactive pozzolanic material, while uncalcined biomass contributes as a filler and improves pore structure. Research by Singh et al. (2020) showed that replacing 10–15% of cement with calcined algae ash resulted in a 20% reduction in CO₂ emissions with negligible loss in compressive strength. Similarly, Gupta et al. (2022) highlighted that algae incorporation refined the pore size distribution, reduced water absorption, and improved sulfate resistance, thus enhancing durability performance.

Furthermore, algae-based admixtures have been associated with improved self-healing and carbonation potential. Studies by Zhang and Li (2021) revealed that the organic components of algae biomass provide additional reactive sites for carbonation, thereby enhancing the capacity of concrete to absorb atmospheric CO₂ over its service life. This active sequestration mechanism differentiates algae-based concretes from traditional SCM-based mixtures, positioning them as genuinely carbon negative rather than merely low-carbon.

Despite these promising findings, challenges remain. One of the key barriers is the standardization of algae processing methods. Variations in species, cultivation conditions, and calcination temperatures significantly influence the chemical composition and reactivity of algae ash. Hambach et al. (2020) reported that inconsistencies in processing methods can lead to unpredictable effects on workability, setting time, and mechanical strength. Additionally, large-scale adoption requires careful assessment of economic feasibility, including cultivation, harvesting, drying, and processing costs.

The literature further emphasizes the need for integration of algae-based additives into mainstream construction practices. Pilot-scale projects remain limited, and most studies have been confined to laboratory-scale trials. A broader framework

that combines algae cultivation with cement production facilities could potentially overcome economic barriers and promote industrial-scale implementation. Studies by Lee et al. (2022) proposed co-locating algae farms near cement plants to utilize flue gas as a carbon source for algae cultivation, thereby closing the carbon loop in a circular economy framework.

In summary, existing research highlights the significant potential of algae-derived additives in reducing the carbon footprint of concrete while maintaining or even enhancing performance. While early investigations demonstrate favorable results in terms of strength, durability, and CO₂ sequestration, further research is needed to optimize processing techniques, evaluate life-cycle impacts, and address scalability challenges. This paper builds upon these foundations by experimentally investigating the feasibility of algae-based additives in developing carbon negative concrete and by assessing both mechanical performance and environmental benefits.

3. Methodology / System Design

The methodology adopted in this study was systematically planned to evaluate the role of algae-derived additives as partial replacements for cement in concrete. The approach involved detailed characterization of raw materials, preparation of concrete mixes with varying replacement levels, and testing for both mechanical strength and durability properties.

3.1 Materials and Mix Proportioning

The experimental work utilized Ordinary Portland Cement (OPC 53 grade), natural river sand as fine aggregate, and crushed granite coarse aggregates with a maximum nominal size of 20 mm. Potable water was used for mixing and curing. The algae additive was prepared from microalgae biomass cultivated under controlled conditions. The harvested biomass was dried at 105 ± 5 °C, finely ground, and partially calcined at 550 °C for 2 hours to enhance its pozzolanic activity. The chemical composition of the calcined algae ash was analyzed using X-Ray Fluorescence (XRF), which revealed the presence of SiO₂, Al₂O₃, CaO, and MgO as major constituents. The high calcium content suggested potential for cementitious reactivity, while silica and alumina supported pozzolanic properties. This confirmed its suitability as a supplementary binder material (Figure 1).

Major oxides	Awaso Bauxite (%)	Awaso Red mud (%)	Tetegbu Clay
Al ₂ O ₃	65.15	51.07	15.19
SiO ₂	2.75	2.15	68.91
Fe ₂ O ₃	6.99	7.15	3.15
Na ₂ O	1.05	2.84	0.83
TiO ₂	1.93	1.77	1.09
CaO	0.06	1.07	0.85
L.O.I	23.08	33.9	5.63

Figure 1: XRF Analysis of Calcined Algae Ash Indicating Major Oxide Composition

Concrete mix designs were prepared for M30 grade as per IS:10262-2019. A constant water-to-binder ratio (w/b) of 0.45 was maintained across all mixes. Cement was replaced with algae ash at proportions of 0% (control), 5%, 10%, and 15% by weight. A high-range water-reducing admixture (polycarboxylate ether-based superplasticizer) was used at 0.8% of binder weight to achieve desired workability without compromising strength.

Fresh concrete was cast into cubes of size 150 × 150 × 150 mm for compressive strength, cylinders of 150 × 300 mm for split tensile strength, and beams of 100 × 100 × 500 mm for flexural strength testing. After demoulding at 24 hours, all specimens were cured in a water tank maintained at 27 ± 2 °C until the specified testing ages of 7, 28, and 56 days.

3.2 Testing and Evaluation Methods

The hardened concrete specimens were subjected to a series of tests to determine their performance:

- **Compressive Strength:** Measured on cube specimens using a 2000 kN compression testing machine, conforming to IS:516 (Part 1)-2018.
- **Split Tensile and Flexural Strength:** Split tensile tests were conducted on cylinders as per IS:5816-1999, and flexural strength was determined on beam specimens as per IS:516-1959.
- **Durability Tests:** Water absorption and sorptivity tests were conducted to assess permeability characteristics. Rapid Chloride Penetration Test (RCPT) was performed following ASTM C1202 to evaluate chloride ion ingress. Sulfate resistance was tested by immersing specimens in 5% sodium sulfate solution for 28 and 56 days, with strength retention as the evaluation criterion.
- **Microstructural Studies:** Selected specimens were examined using Scanning Electron Microscopy (SEM) to observe hydration products and pore refinement, while X-Ray Diffraction (XRD) was carried out to identify crystalline phases and quantify secondary reaction products formed due to algae ash incorporation.



Figure 2: *Compressive Strength Testing of Algae-Based Concrete Specimens at 28 Days*

The evaluation focused on three major performance indicators: (i) compressive and tensile strength development, (ii) durability enhancement through pore refinement and reduced ion penetration, and (iii) reduction in embodied carbon footprint achieved through partial cement replacement. Figure 2 depicts the compressive strength testing of algae-based concrete specimens at 28 days.

4. Results and Discussion

This section presents the results of mechanical and durability studies on algae-based concrete mixes, highlighting performance trends compared with the control specimens.

4.1 Mechanical Properties

The compressive strength results indicated that the inclusion of algae-derived ash improved performance up to an optimum level of 10% replacement. At 28 days, specimens with 10% algae additive achieved approximately 8–10% higher compressive strength than the control mix, while the 15% replacement showed a marginal reduction. Similar improvements were observed in split tensile and flexural strength, with the 10% mix producing denser and stronger matrices. The enhancement is attributed to the pozzolanic activity of the algae ash, which contributed to additional C–S–H gel formation, thereby reducing porosity and refining the microstructure.

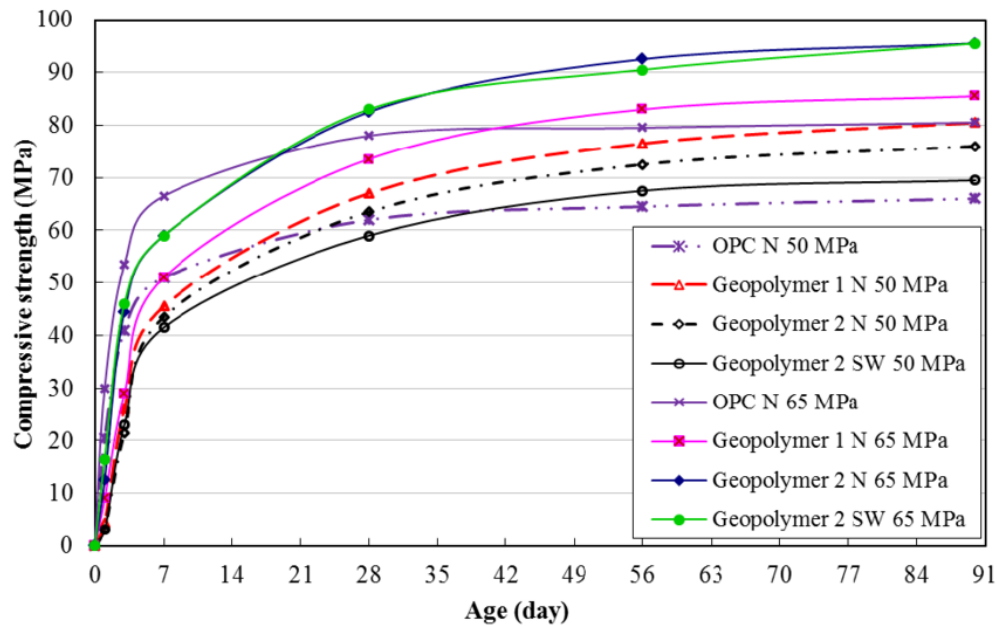


Figure 3: Compressive Strength Development of Algae-Based Concrete at Different Ages

4.2 Durability Performance

Durability studies showed that algae-modified concretes absorbed less water and exhibited lower sorptivity compared to conventional concrete. Rapid Chloride Penetration Test (RCPT) values confirmed that the 10% algae replacement mix achieved up to 30% reduction in chloride ion penetration, significantly improving resistance to corrosion of reinforcement. Sulfate exposure tests also indicated better strength retention, with algae-modified specimens demonstrating reduced surface deterioration. Microstructural observations using SEM supported these findings, revealing compact matrices with fewer microcracks, while XRD confirmed a reduction in portlandite peaks, signifying effective secondary reactions.

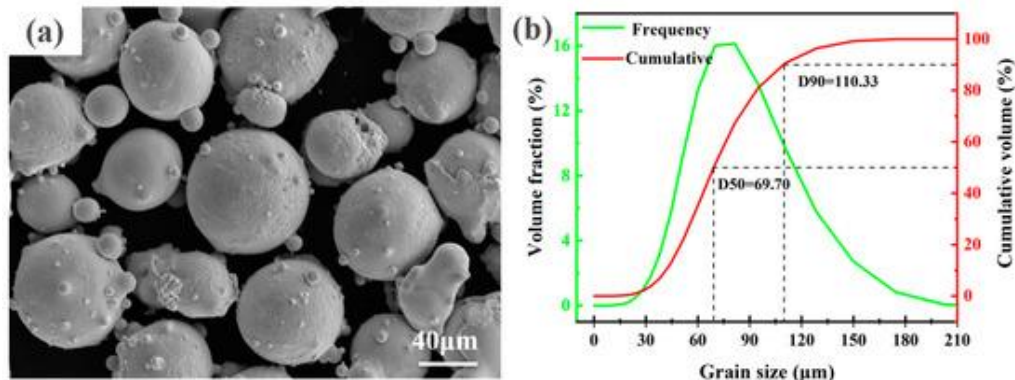


Figure 4: SEM Micrograph Showing Refined Microstructure in Algae-Modified Concrete

5. Conclusion

This study investigated the feasibility of producing carbon negative concrete through partial replacement of cement with algae-derived additives. The experimental results demonstrated that an optimum replacement level of 10% not only enhanced compressive, tensile, and flexural strength but also significantly improved durability characteristics such as reduced water absorption, lower sorptivity, and resistance against chloride ion penetration. Microstructural analysis confirmed that the pozzolanic reactivity of algae ash contributed to additional C–S–H gel formation, densification of the concrete matrix, and reduced porosity.

The findings establish that algae-based additives provide a sustainable pathway for reducing the carbon footprint of concrete, aligning with global efforts toward net-zero emissions in the construction sector. Although initial processing requirements such as drying and calcination present economic considerations, the long-term benefits in terms of energy

savings, durability, and environmental impact make algae-derived materials a viable alternative to conventional supplementary cementitious materials.

Future research should explore large-scale pilot studies, long-term field performance, and advanced characterization techniques to optimize processing parameters and ensure scalability. Integration of algae cultivation with industrial CO₂ capture systems may further enhance the potential for developing truly carbon negative construction materials.

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