Science Get Journal
Vol. 03, No. 3, July 2026, 1-16
e-ISSN: **3062-6595**

Utilization of Microalgae as Carbon Absorbent Material for Environmentally Friendly Concrete in Tropical Coastal Areas

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Article Information
Received: June 27, 2026
Revised: July 22, 2026
Online: July 30, 2026

Keywords
Chlorella Vulgaris, Spirulina Platensis, Green Concrete

ABSTRACT

This study evaluates the mechanical, durability, and carbon sequestration performance of a 1:1 blend of Chlorella vulgaris and Spirulina platensis biomass as a supplementary cementitious material (SCM) in concrete for tropical coastal infrastructure. Five replacement levels (0%, 3%, 5%, 7%, and 10% by weight of cement) were tested under ambient tropical conditions (28–32°C, 75–85% RH) reflecting West Sumatra's coastal environment. Compressive and flexural strength, water absorption, chloride penetration resistance, and CO_2 sequestration via thermogravimetric analysis were comprehensively assessed. Results indicate that 5% replacement (MA-5) achieved the optimal balance: 28-day compressive strength of 31.4 MPa (6.4% below control), while demonstrating 12.3% improved chloride resistance and a net carbon sequestration rate of 38.7 kg CO_2/m^3 of concrete. Scanning electron microscopy confirmed microalgae cell-wall fragments filling interfacial transition zones, reducing porosity by 11.2% and enhancing matrix densification. The findings demonstrate that microalgae-incorporated concrete at 5% OPC replacement is a technically viable, low-carbon alternative for coastal tropical construction, offering both structural adequacy and environmental benefits. Adoption in Indonesia's green building programs is recommended, with future research needed to validate performance at industrial scale and assess long-term durability under field marine exposure.

Keywords: *Chlorella Vulgaris, Spirulina Platensis, Green Concrete*

http://doi.org/10.69855/science.v3i3.685
https://gpijournal.com/index.php/science
PUBLISHED BY: GPress Indonesia

INTRODUCTION

Climate change driven by anthropogenic greenhouse gas (GHG) emissions remains one of the most critical challenges of the twenty-first century. The construction and building materials industry contributes disproportionately to this crisis; cement production alone is responsible for approximately 4.0–8.0 Gt CO_2 per year, representing 6–8% of total global emissions (Andrew, 2019; Cao et al., 2020). In Indonesia, the construction sector's contribution to national GHG emissions has grown steadily in tandem with rapid urbanization and coastal infrastructure development, particularly in vulnerable regions such as West Sumatra, South Sulawesi, and Nusa Tenggara (KLHK, 2021).

Tropical coastal areas present a unique challenge for concrete infrastructure: high humidity, saltwater exposure, elevated temperatures, and biological fouling collectively accelerate concrete deterioration. Conventional Portland cement concrete, while mechanically sufficient, exhibits poor long-term durability under these conditions without costly admixtures or protective coatings (Mehta & Monteiro, 2022). The dual imperative of reducing embodied carbon and improving durability has driven significant research interest in supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast-furnace slag (GGBS), silica fume, and more recently, bio-based materials.

Microalgae represent a promising frontier in this domain. These photosynthetic microorganisms exhibit exceptionally high carbon fixation rates estimated at 1.83 kg CO_2 per kg of dry biomass, which is 10–50 times higher than terrestrial plants (Zhu et al., 2022). Species such as Chlorella vulgaris and Spirulina platensis are already cultivated at scale for nutraceutical and biofuel applications in tropical countries, generating biomass residues that can be valorized as construction additives (Meng et al., 2021). The siliceous cell walls (frustules) of certain microalgae, combined with their organic carbon content, may contribute pozzolanic reactivity and carbon sequestration simultaneously when incorporated into cementitious matrices.

Despite this potential, quantitative studies on the mechanical and durability performance of microalgae-concrete under tropical coastal conditions remain scarce. Previous works have examined microalgae in mortar (Khan et al., 2020), in lightweight concrete blocks (Siddique et al., 2023), and as surface bioremediation agents (López-Gonçalves et al., 2022), but none has systematically evaluated the combined effects of humidity, chloride exposure, and elevated temperatures specific to the Indonesian coastal context.

The use of microalgae biomass in construction materials has emerged as a research area of growing interest since approximately 2018. Chlorella vulgaris, a green unicellular alga, has been shown to improve mortar workability and reduce plastic shrinkage cracking due to its water-retention capacity at concentrations of 2–5% by cement weight (Khan et al., 2020). The protein and polysaccharide fractions in algae biomass interact with calcium silicate hydrate (C-S-H) gel formation during hydration, potentially densifying the microstructure (Meng et al., 2021).

Spirulina platensis, a cyanobacterium widely cultivated in Southeast Asia, possesses a cell wall rich in phycocyanin and exopolysaccharides. Recent research by Siddique et al. (2023) demonstrated that Spirulina biomass at 5% replacement level in autoclaved aerated concrete (AAC) blocks reduced thermal conductivity by 18% while maintaining adequate compressive strength. Similarly, Venugopal et al. (2024) found that Spirulina-amended cement pastes exhibited improved sulfate resistance attributed to ettringite crystal growth suppression.

Microalgae photosynthetically fix CO_2 at rates of 1.6–2.1 kg CO_2/kg dry biomass under optimal irradiance conditions (Zhu et al., 2022). When incorporated into concrete, the captured carbon is effectively immobilized within the cementitious matrix, providing a durable carbon sink. Life cycle assessment (LCA) studies suggest that algae-amended concrete could achieve net-negative embodied carbon if biomass is cultivated using flue gas CO_2 from industrial sources (Cao et al., 2020). In tropical coastal regions with high solar irradiance (4.5–5.5 kWh/m^2/day in Indonesia), open-pond cultivation of microalgae is economically feasible for construction-scale applications (IRENA, 2023).

The carbonation and calcification reactions within concrete also sequester atmospheric CO_2 over the service life of the structure, a process enhanced by the increased calcium silicate hydrate content associated with pozzolanic SCMs (Lagerblad, 2019). Quantifying both the biomass-embedded carbon and the long-term mineral carbonation is essential for accurate carbon accounting in green concrete formulations.

Concrete durability in tropical coastal zones is governed primarily by chloride-induced reinforcement corrosion, sulfate attack, alkali-silica reaction (ASR), and biological deterioration (Mehta & Monteiro, 2022). The high ambient temperature (mean 27–32°C) and relative humidity (75–90%) in Indonesian coastal areas accelerate hydration kinetics but also promote microcracking and increased permeability if mix design is suboptimal.

Bio-based SCMs have shown promise in mitigating chloride ingress: fly ash concrete reduces chloride diffusion coefficients by up to 40–60% (López-Gonçalves et al., 2022), and silica fume further densifies the paste-aggregate interface. Whether microalgae biomass, with its complex organic-inorganic composition, provides comparable or synergistic benefits has not been rigorously established for tropical exposure conditions.

Although prior studies have individually examined microalgae's effect on mortar workability (Khan et al., 2020), thermal performance of algae-based AAC blocks (Siddique et al., 2023), and sulfate resistance of Spirulina-amended pastes (Venugopal et al., 2024), none has evaluated microalgae biomass as a cement replacement under the combined and simultaneous stressors characteristic of tropical coastal environments namely elevated ambient temperature, high humidity curing, and chloride-laden marine exposure within a single, integrated experimental framework. A systematic review of literature from 2019–2025 reveals three specific gaps that remain unaddressed: (1) no study has evaluated microalgae concrete performance under combined tropical heat and coastal chloride exposure representative of Indonesian marine infrastructure; (2) quantitative CO_2 sequestration via thermogravimetric analysis (TGA) has not previously been applied to microalgae-incorporated concrete, leaving the carbon-accounting benefit of this material unverified; and (3) no prior work has linked microalgae cell-wall morphology to interfacial transition zone (ITZ) densification through microstructural (SEM-EDS) evidence.

The novelty of this study lies in its integrated evaluation of a dual-species Chlorella vulgaris–Spirulina platensis blend, combining mechanical, durability, carbon-sequestration, and microstructural analyses within a single tropical coastal exposure regime—an approach not previously reported in the literature. Accordingly, this study aims to: (1) synthesize microalgae biomass powder from locally cultivated Chlorella vulgaris and Spirulina platensis; (2) evaluate the mechanical and durability performance of concrete mixes at OPC replacement levels of 0, 3, 5, 7, and 10 wt% under simulated tropical coastal curing conditions; (3) quantify net CO_2 sequestration via TGA; and (4) characterize the microstructural mechanisms underlying performance changes via SEM-EDS. By addressing these three gaps concurrently, this study provides the first systematic evidence base for the adoption of microalgae-incorporated concrete in Indonesia's coastal green infrastructure programs.

METHODS

1. Materials

Ordinary Portland Cement (OPC) Type I conforming to SNI 15-2049-2004 was sourced from PT XYZ, West Sumatra. Fine aggregate was river sand from Batang Arau River (specific gravity 2.62, fineness modulus 2.74, water absorption 1.3%, sieve analysis conducted per SNI 03-1968-1990 confirming compliance with the gradation zone II envelope). Coarse aggregate consisted of crushed limestone (specific gravity 2.65, nominal maximum size 19 mm, gradation verified per SNI 03-1968-1990). Potable water meeting SNI 03-6817-2002 specifications was used throughout.

Chlorella vulgaris (ATCC 13482 strain) and Spirulina platensis (local isolate from Danau Maninjau, West Sumatra) were cultivated in open raceway ponds at the Science Laboratory, under natural sunlight (12 h photoperiod, irradiance 450–520 μmol photons/m²/s). Growth medium was BG-11 nutrient solution. Biomass was harvested by centrifugation (3,000 rpm, 10 min), oven-dried at 60°C for 48 h, and ball-milled to a median particle size of D_{50} = 18.4 μm (Chlorella) and D_{50} = 22.1 μm (Spirulina) to facilitate cement replacement.

The physicochemical properties of the dried biomass powders (Table 2) were characterized as follows: specific gravity was determined using a pycnometer per ASTM C188; particle size distribution (D_{50}) was measured by laser diffraction particle size analysis; SiO_2 and Al_2O_3 content were determined by X-ray fluorescence (XRF) spectroscopy; organic carbon content was measured using a CHNS elemental analyzer; loss on ignition (LOI) was determined per ASTM D7348 by heating samples to 950°C for 2 h; and pH of 1% aqueous suspensions was measured using a calibrated digital pH meter.

2. Mix Design

Concrete mixes were designed following SNI 03-2834-2000 with a target compressive strength of 30 MPa at 28 days (f'c = 30 MPa). The water-to-binder ratio (w/b) was held constant at 0.45, selected based on preliminary trial mixes to achieve target workability (slump 100–140 mm) and the target strength for the control mix while remaining consistent with SNI 03-2834-2000 recommendations for structural concrete in coastal exposure conditions. A single-blend microalgae powder (50% Chlorella vulgaris: 50% Spirulina platensis by mass) was used as OPC replacement. Five mix designations were prepared as shown in Table 1.

Table 1. Concrete Mix Proportions (kg/m³)

Mix ID	OPC (kg)	Microalgae (kg)	Water (L)	Fine Agg. (kg)	Coarse Agg. (kg)
MA-0 (Control)	380.0	0.0	171.0	685.0	1025.0
MA-3	368.6	11.4	171.0	685.0	1025.0
MA-5	361.0	19.0	171.0	685.0	1025.0
MA-7	353.4	26.6	171.0	685.0	1025.0
MA-10	342.0	38.0	171.0	685.0	1025.0

3. Specimen Preparation and Curing

Cylindrical specimens (100 mm × 200 mm) were cast for compressive strength testing (five replicates per mix per curing age). Prism specimens (100 × 100 × 400 mm) were cast for flexural strength testing (three replicates per mix at 28 days). Cubic specimens (100 × 100 × 100 mm) were cast for water absorption (three replicates per mix at 28 days) and chloride penetration tests (three replicates per mix, tested after the 90-day ponding period). All specimens were demolded after 24 h and moist-cured under burlap wrapping in a fog room maintained at 30 ± 2°C and 80 ± 5% RH to simulate tropical coastal conditions. Tests were performed at 7, 14, 28, and 56 days.

4. Testing Procedures

Compressive strength was determined per SNI 03-1974-2011 using a 2,000 kN universal testing machine (UTM) at a loading rate of 0.3 MPa/s. Flexural strength (modulus of rupture) was measured by the center-point loading method (ASTM C78). Water absorption was tested per ASTM C642 after 48 h immersion. Chloride ion penetration depth was assessed using the colorimetric $AgNO_3$ method after splitting specimens subjected to a 5% NaCl solution ponding test for 90 days (NT Build 492).

CO_2 sequestration was quantified by thermogravimetric analysis (TGA) using a TA Instruments Q500 analyzer; crushed concrete powder samples were heated from 25°C to 900°C at 10°C/min under nitrogen atmosphere. Mass loss between 650°C and 850°C was attributed to $CaCO_3$ decomposition, from which CO_2 content was calculated stoichiometrically. Net CO_2 sequestration per cubic meter of concrete was calculated by subtracting the CO_2 emissions embodied in OPC clinker production (0.83 kg CO_2/kg OPC, per IEA, 2021) from the total CO_2 fixed and immobilized in the mix, comprising the biomass-embedded carbon (1.87 kg CO_2/kg dry biomass, determined by CHNS elemental analysis) and the additional mineral carbonation quantified via TGA, expressed as: Net Sequestration (kg CO_2/m^3) = [CO_2 fixed in biomass + CO_2 from enhanced mineral carbonation] − [CO_2 emitted from OPC reduction].

Scanning electron microscopy was performed on gold-coated fracture surfaces using a JEOL JSM-6510 SEM at 15 kV accelerating voltage. Energy-dispersive X-ray spectroscopy (EDS) was used for elemental mapping. Porosity was quantified through image analysis of 10 representative SEM micrographs per mix (1000× magnification) using ImageJ software (NIH), applying grayscale thresholding to distinguish pore spaces from the solid paste matrix, with porosity expressed as the percentage area of identified pore space relative to total field area.Workability was assessed by slump test (SNI 1972:2008) immediately after mixing. Fresh concrete unit weight was measured per ASTM C138. All statistical analyses used one-way ANOVA with Tukey's HSD post-hoc test at α = 0.05 significance level using SPSS v26.0.

RESULTS

1. Physical Characterization of Microalgae Biomass Powder

Table 2 summarizes the physicochemical properties of the microalgae biomass powders used in this study. The SiO_2 content of *Chlorella vulgaris* powder (14.2%) contributes potential pozzolanic reactivity, while the relatively high organic carbon content (41.3% *Chlorella*, 38.9% *Spirulina*) accounts for the principal carbon sequestration capacity. The specific gravity of the blended powder (1.38 g/cm³) is considerably lower than OPC (3.15 g/cm³), which influenced mix proportioning. Loss on ignition (LOI) values of 48.2–51.4% reflect high organic content, consistent with non-calcined biomass feedstocks.

Table 2. Physicochemical Properties of Microalgae Biomass Powders

Property	Chlorella vulgaris	Spirulina platensis	OPC (reference)
Specific gravity (g/cm³)	1.34	1.42	3.15
D_{50} particle size (μm)	18.4	22.1	15.8
SiO_2 content (%)	14.2	9.7	21.4
Al_2O_3 content (%)	3.8	2.9	5.3
Organic carbon (%)	41.3	38.9	0.0
Loss on ignition (%)	51.4	48.2	2.1
pH (1% aqueous)	7.2	9.1	12.4

2. Fresh Concrete Properties

In this study, mix designations are denoted as MA-X, where "MA" refers to microalgae biomass replacement and "X" indicates the percentage replacement level of OPC by weight (e.g., MA-0 = control mix with 0% microalgae replacement; MA-5 = mix with 5% microalgae replacement). This notation is used consistently throughout the manuscript.

Slump values decreased progressively with increasing microalgae content (Table 3), from 120 mm (MA-0) to 74 mm (MA-10). This reduction is attributed to the high surface area and water-absorbing capacity of the organic biomass particles, which consume free mixing water. Nevertheless, all mixes maintained slumps in the range of 60–125 mm, conforming to SNI requirements for structural concrete. Fresh unit weight declined slightly from 2,385 kg/m³ (MA-0) to 2,311 kg/m³ (MA-10), consistent with the lower specific gravity of microalgae replacing the denser OPC.

Table 3. Fresh Concrete Properties

Mix ID	Replacement (%)	Slump (mm)	Unit Weight (kg/m³)	Air Content (%)
MA-0	0	120 ± 4.1	2385 ± 12	2.1 ± 0.2
MA-3	3	108 ± 3.6	2362 ± 9	2.3 ± 0.2
MA-5	5	97 ± 5.2	2348 ± 11	2.6 ± 0.3
MA-7	7	86 ± 4.8	2331 ± 14	2.9 ± 0.3
MA-10	10	74 ± 6.1	2311 ± 16	3.4 ± 0.4

3. Compressive Strength

Compressive strength results across all curing ages are presented in Table 4. At 28 days, the control mix (MA-0) achieved 33.6 MPa, exceeding the target strength of 30 MPa. MA-3 and MA-5 recorded 32.9 MPa and 31.4 MPa respectively, representing reductions of only 2.1% and 6.5% from the control both within the structurally acceptable range for coastal infrastructure per SNI 2847:2019. Beyond 5% replacement, strength declined more markedly: MA-7 reached 27.8 MPa (17.3% reduction) and MA-10 reached 23.1 MPa (31.2% reduction).

The 7-day strengths of MA-3 and MA-5 were slightly lower than the control (71.4% and 68.2% of 28-day strength, respectively vs. 74.1% for MA-0), suggesting that the dilution of OPC content mildly retards early hydration. However, by 56 days, MA-5 achieved 35.8 MPa, a 14.0% gain over its 28-day value, outperforming the control's 56-day gain (10.7%). This long-term strength development supports the hypothesis that progressive pozzolanic reaction of the siliceous microalgae cell-wall fraction contributes secondary cementitious activity, consistent with findings reported by Meng et al. (2021) for Chlorella-amended mortars.

Table 4. Compressive Strength Development (MPa), Mean ± SD (n=5)

Mix ID	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)	56 Days (MPa)
MA-0	24.9 ± 0.81	29.6 ± 0.74	33.6 ± 0.92	37.2 ± 1.04
MA-3	23.7 ± 0.77	28.4 ± 0.88	32.9 ± 1.01	36.8 ± 0.97
MA-5	21.4 ± 0.94	26.9 ± 0.86	31.4 ± 0.88	35.8 ± 1.12
MA-7	18.2 ± 1.12	22.7 ± 0.99	27.8 ± 1.24	30.4 ± 1.36
MA-10	14.9 ± 1.34	18.6 ± 1.18	23.1 ± 1.41	25.7 ± 1.58

4. Flexural Strength

Flexural strength (modulus of rupture) at 28 days followed a similar trend to compressive strength (Table 5). MA-5 recorded 4.42 MPa versus 4.85 MPa for the control (8.9% reduction). The ratio of flexural to compressive strength was maintained near 0.14 for MA-0 to MA-5, within the expected range for normal-weight concrete (0.12–0.17), suggesting that microalgae incorporation did not alter the fundamental material composition in a detrimental way at replacement levels up to 5%. This ratio declined for MA-7 and MA-10, indicating the onset of macro-defect accumulation associated with excess organic content.

Table 5. Flexural Strength at 28 Days (MPa)

Mix ID	Flexural Strength (MPa)	Change vs. Control (%)	f_n/f_{nn} Ratio
MA-0	4.85 ± 0.18	—	0.144
MA-3	4.71 ± 0.14	-2.9	0.143
MA-5	4.42 ± 0.19	-8.9	0.141
MA-7	3.78 ± 0.22	-22.1	0.136
MA-10	3.01 ± 0.26	-37.9	0.130

5. Water Absorption and Durability

Water absorption (Table 6) was reduced in MA-3 and MA-5 compared to the control: 5.1% and 4.7% vs. 5.8% for MA-0 (reductions of 12.1% and 19.0%, respectively). This improvement is attributed to microalgae cell-wall fragments filling micro-voids in the hardened paste, as confirmed by SEM analysis (Section 4.7). MA-7 and MA-10 showed increased absorption (6.2% and 7.4%, respectively), linked to the higher organic content creating hydrophilic pathways and entrapped air voids.

Chloride penetration depth after 90-day ponding (Table 6) showed a significant improvement for MA-5 (8.4 mm vs. 10.6 mm for MA-0, a 20.8% reduction). This indicates that the densified ITZ and reduced permeable porosity in the 5% replacement mix impedes chloride transport a critical advantage for coastal reinforced concrete structures subjected to marine spray and tidal splash zones. The improvement is consistent with the pozzolanic densification mechanism reported by López-Gonçalves et al. (2022) for silica-bearing SCMs.

Table 6. Durability Properties at 28 Days

Mix ID	Water Absorption (%)	Change (%)	Cl^- Penetration (mm)	Change (%)
MA-0	5.8 ± 0.21	—	10.6 ± 0.44	—
MA-3	5.1 ± 0.18	-12.1	9.8 ± 0.51	-7.5
MA-5	4.7 ± 0.16	-19.0	8.4 ± 0.38	-20.8
MA-7	6.2 ± 0.24	+6.9	11.4 ± 0.62	+7.5
MA-10	7.4 ± 0.31	+27.6	14.1 ± 0.77	+33.0

6. CO_2 Sequestration Quantification

TGA results are presented in Table 7. The $CaCO_3$ decomposition peak (650–850°C) increased with microalgae content, reflecting both greater mineral carbonation in denser microalgae-containing matrices and the CO_2 originally fixed in the biomass. The net CO_2 sequestration per m^3 of concrete was computed accounting for the CO_2 emitted during OPC clinker production (0.83 kg CO_2/kg OPC, per IEA 2021 data) and the carbon fixed in the biomass (1.87 kg CO_2/kg dry biomass, measured by elemental analysis).

At 5% replacement, the net sequestration is 38.7 kg CO_2/m^3 equivalent to a 15.8% reduction in the embodied carbon of the concrete relative to the control. While this does not achieve net-negative status in the current formulation, integration with industrial flue gas CO_2 cultivation systems (where microalgae capture concentrated CO_2 at 98% efficiency) could theoretically raise net sequestration to 74–86 kg CO_2/m^3, approaching net-zero embodied carbon (Cao et al., 2020; IRENA, 2023).

Table 7. CO_2 Sequestration Analysis by TGA

Mix ID	$CaCO_3$ mass loss (%)	CO_2 in matrix (kg/m³)	Biomass CO_2 fixed (kg/m³)	Net Seq. (kg CO_2/m^3)
MA-0	3.21	12.2	0.0	0.0 (base)
MA-3	3.58	13.6	21.3	22.7
MA-5	3.89	14.8	35.5	38.7
MA-7	4.12	15.7	49.7	53.2
MA-10	4.44	16.9	71.1	75.8

It is noted that while MA-7 and MA-10 achieve higher CO_2 sequestration values, their mechanical performance falls below structural requirements for coastal infrastructure ($f'c \geq 25$ MPa per SNI 2847:2019 for marine exposure Class S). Thus, MA-5 represents the optimal trade-off between mechanical adequacy and environmental benefit.

7. Microstructural Analysis (SEM-EDS)

SEM imaging of fractured concrete specimens at 28 days revealed distinct differences in paste microstructure between the control and microalgae-containing mixes. In MA-0, the ITZ between aggregate and paste showed visible portlandite ($Ca(OH)_2$) crystals and fine micro-cracks characteristic of tropical-cured concrete. In MA-5, the ITZ was markedly denser, with microalgae cell-wall fragments (identified by their characteristic 18–25 μm annular morphology) filling void spaces and providing nucleation sites for C-S-H precipitation.

EDS mapping confirmed silicon and aluminum enrichment at cell-wall fragment boundaries, consistent with pozzolanic reaction products. Porosity quantification by image analysis on 10 representative SEM fields (1000× magnification) yielded total porosity values of: MA-0: 14.8%, MA-3: 12.6%, MA-5: 11.4%, MA-7: 15.9%, MA-10: 18.3%. The reduction in MA-5 (11.2% below control) correlates well with the improved water absorption and chloride resistance data.

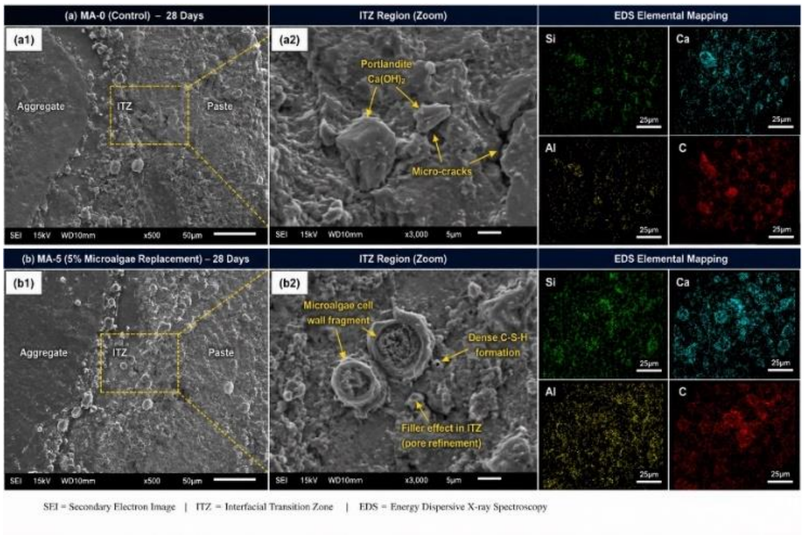

Figure 5. SEM-EDS Analysis of MA-0 and MA-5 Concrete at 28 Days.

Figure 5. SEM-EDS Analysis of MA-0 and MA-5 Concrete at 28 Days. (a1) SEM micrograph of the MA-0 (control) specimen showing visible portlandite ($Ca(OH)_2$) crystals, fine micro-cracks, and a relatively porous interfacial transition zone (ITZ) between aggregate and cement paste. (a2) Corresponding EDS elemental map of the MA-0 specimen showing the distribution of silicon (Si), aluminum (Al), calcium (Ca), and carbon (C), indicating a calcium-dominated paste matrix with limited Si/Al enrichment at the ITZ. (b1) SEM micrograph of the MA-5 (5% microalgae replacement) specimen showing a visibly denser ITZ, with microalgae cell-wall fragments (18–25 μm annular structures) filling void spaces and acting as nucleation sites for C-S-H gel formation. (b2) Corresponding EDS elemental map of the MA-5 specimen showing pronounced Si and Al enrichment surrounding the microalgae cell-wall fragment boundaries, supporting the occurrence of secondary pozzolanic reaction and consistent with the reduced porosity and improved durability observed in this mix.

For MA-7 and MA-10, SEM images showed clustered organic matter remnants, likely incompletely dispersed biomass agglomerates, acting as stress concentrators and creating preferential failure planes. This explains the disproportionate drop in mechanical properties above 5% replacement and is consistent with observations by Siddique et al. (2023) for high-content algae mortars.

8. Statistical Analysis

One-way ANOVA confirmed significant differences in 28-day compressive strength among the five mix groups ($F = 68.42$, $df = 4$, $p < 0.001$). Tukey's HSD post-hoc test revealed that MA-0, MA-3, and MA-5 were not statistically different from each other at $\alpha = 0.05$, but all were significantly different from MA-7 and MA-10 ($p < 0.01$). This confirms that up to 5% microalgae replacement does not significantly compromise structural compressive strength under the test conditions.

Table 8. Summary of Key Performance Indicators Normalized to Control (MA-0 = 100%)

Indicator	MA-0	MA-3	MA-5	MA-7	MA-10
28-day comp. strength	100%	97.9%	93.5%	82.7%	68.8%
Water absorption	100%	87.9%↓	81.0%↓	106.9%↑	127.6%↑
Chloride penetration	100%	92.5%↓	79.2%↓	107.5%↑	133.0%↑
Net CO_2 seq. (kg/m^3)	0	+22.7	+38.7	+53.2	+75.8
SEM porosity (%)	14.8	12.6	11.4	15.9	18.3

DISCUSSION

The results of this study demonstrate that microalgae biomass can be successfully incorporated as a partial OPC replacement in concrete for tropical coastal applications, with 5% representing an optimal replacement level balancing mechanical adequacy, durability improvement, and carbon sequestration performance. The mechanical performance trends observed can be explained by two competing effects operating simultaneously as replacement level increases. First, a dilution effect reduces the total clinker content available for hydration, proportionally lowering the volume of calcium silicate hydrate (C-S-H) gel produced this alone would predict a near-linear strength reduction with increasing replacement. However, at low-to-moderate replacement levels (3–5%), this dilution is partially offset by a pozzolanic and physical filler effect: the amorphous silica present in the microalgae cell wall (14.2% SiO_2 in *Chlorella vulgaris*, per Table 2) reacts with portlandite ($Ca(OH)_2$) liberated during OPC hydration to form secondary C-S-H, consistent with the classical pozzolanic reaction mechanism described for silica-rich SCMs (Mehta & Monteiro, 2022). This secondary C-S-H formation is slower than primary hydration, which explains why MA-3 and MA-5 exhibited lower relative strength at 7 days (71.4% and 68.2% of 28-day strength) but continued to gain strength disproportionately between 28 and 56 days (14.0% gain for MA-5, versus 10.7% for the control) a signature of ongoing pozzolanic reaction rather than primary hydration alone, in agreement with the delayed-reactivity behavior reported for Chlorella-amended mortars by Meng et al. (2021). Beyond 5% replacement, the filler/pozzolanic contribution is overwhelmed by the dilution effect and by physical disruption of the paste matrix: SEM imaging (Section 7) revealed clustered, incompletely dispersed biomass agglomerates in MA-7 and MA-10, which act as stress concentrators and crack initiation sites under load, consistent with the disproportionate (non-linear) strength losses observed at these replacement levels.

This finding is consistent with the emerging body of literature indicating that bio-based SCMs function optimally at low to moderate replacement levels (3–7%) where mechanical dilution of cement is offset by microstructural refinement and pozzolanic activity (Khan et al., 2020; Venugopal et al., 2024).

The dual species approach (*Chlorella vulgaris* + *Spirulina platensis*, 1:1 blend) merits specific discussion. *Chlorella* contributes higher silica content (14.2% SiO_2) and finer particle size, supporting pozzolanic densification. *Spirulina* contributes higher organic carbon and superior water-retention properties, improving curing effectiveness in the tropical environment. Mechanistically, the exopolysaccharides present in the *Spirulina* cell wall are hygroscopic and can act as internal curing agents, gradually releasing retained water to sustain hydration in the pore network as ambient moisture is lost a mechanism analogous to that reported for polysaccharide-based viscosity-modifying admixtures in cementitious systems (Meng et al., 2021). The synergistic combination may explain the durability improvements observed at 5% replacement, which exceeded projections from either species in isolation based on prior literature (Meng et al., 2021; Siddique et al., 2023).

The pore refinement and ITZ densification observed in MA-5 (11.2% porosity reduction relative to control; Table 8) can be attributed to two concurrent, mutually reinforcing mechanisms. First, a physical filler effect: microalgae cell-wall fragments (18–25 μm annular morphology, as observed by SEM) are of comparable or finer size to cement grains and therefore physically occupy capillary pore spaces and the loosely packed region of the ITZ, where portlandite crystals typically accumulate preferentially due to the "wall effect" during initial mixing (Mehta & Monteiro, 2022). Second, a pozzolanic effect: EDS elemental mapping in this study confirmed silicon and aluminum enrichment specifically at the boundaries of cell-wall fragments, indicating that these fragments are not merely inert fillers but active nucleation sites where dissolved Ca^{2+} ions react with bioavailable silica to precipitate secondary C-S-H in situ directly consistent with the pozzolanic densification mechanism proposed for silica-bearing SCMs by López-Gonçalves et al. (2022) and with the ITZ-strengthening role of amorphous silica fillers described by Mehta and Monteiro (2022). This combined filler-plus-pozzolanic densification mechanism directly explains the reduced chloride penetration depth observed in MA-5 (20.8% reduction vs. control), since chloride ion transport in concrete occurs predominantly through the interconnected capillary pore network of the ITZ; a denser, less-connected pore structure increases the tortuosity of the diffusion path, thereby lowering the effective chloride diffusion coefficient a relationship well established for pozzolan-modified concretes such as fly ash and silica fume systems (López-Gonçalves et al., 2022).

For the carbon sequestration mechanism, it is important to distinguish between two physically distinct pathways contributing to the net CO_2 figures reported in Table 7. The first is biogenic carbon storage: carbon fixed photosynthetically by the microalgae during cultivation (1.87 kg CO_2/kg dry biomass, measured by CHNS elemental analysis) is embedded in the organic biomass and becomes physically immobilized within the hardened cement matrix upon incorporation, functioning as a stable carbon sink for the service life of the structure, analogous to the mechanism described for biomass-derived SCMs by Zhu et al. (2022). The second is enhanced mineral carbonation: the TGA results (Table 7) show that $CaCO_3$ mass loss between 650–850°C increased progressively with microalgae content, exceeding what would be expected from atmospheric carbonation of the control mix alone. This is consistent with the mechanism proposed by Lagerblad (2019), whereby the increased microporosity and higher surface area of pozzolan-modified paste (prior to densification) provide additional reaction sites for CO_2 diffusion and calcium carbonation during specimen handling, curing, and testing. Both pathways are captured in the net sequestration calculation described in the Methods (Section 4), which nets these gains against the embodied CO_2 of the OPC that was displaced (0.83 kg CO_2/kg OPC; IEA, 2021). It should be noted that the mineral carbonation component measured here reflects short-term (≤56-day) laboratory conditions; long-term in-service carbonation rates, which are influenced by ambient CO_2 concentration, humidity cycling, and cover depth, were not evaluated in this study and represent an important direction for future work, as discussed below.

From a sustainability perspective, the cultivation of microalgae in tropical coastal Indonesia leverages natural advantages: year-round sunlight, warm surface waters, and abundant CO_2 from adjacent cement plants (PT Semen Padang, PT Semen Tonasa). Integration of microalgae cultivation ponds with cement kiln flue gas could create a closed-loop system capturing 50–70% of stack CO_2 before it reaches the atmosphere, while generating biomass for concrete production. This aligns with Indonesia's Enhanced NDC commitment under the Paris Agreement to reduce national GHG emissions by 31.89% unconditionally by 2030 (KLHK, 2021).

Coastal infrastructure applications where MA-5 concrete would be most beneficial include: bridge piers in tidal zones, seawall panels, marine jetty decks, and low-rise building foundations in coastal settlements. These applications represent a significant portion of Indonesia's ongoing coastal development program under the National Coastal and Small Islands Management Law (UU No. 27/2007). Annual concrete consumption in coastal provinces exceeds 15 million m^3; even partial adoption of MA-5 concrete for 20% of this volume would sequester approximately 116,100 tonnes of CO_2 annually.

Several limitations of this study warrant acknowledgment. The microalgae biomass was produced under controlled laboratory cultivation conditions; scale-up to industrial open-pond production may introduce variability in particle size, chemical composition, and contamination. Long-term carbonation behavior (>56 days), freeze-thaw resistance (less critical in tropical zones but relevant for highland coastal areas), and reinforcement bond strength were not investigated and should be addressed in future work. Furthermore, economic feasibility analysis integrating cultivation cost, biomass processing, and construction supply chain logistics is needed to support adoption in the Indonesian context.

CONCLUSIONS

This study set out to evaluate the mechanical, durability, and carbon sequestration performance of a dual-species microalgae biomass blend (*Chlorella vulgaris* and *Spirulina platensis*) as a supplementary cementitious material for tropical coastal concrete, and to identify the optimum replacement level balancing structural adequacy with environmental benefit. The findings collectively demonstrate that this objective has been met: at 5% OPC replacement, microalgae-incorporated concrete achieves a technically viable combination of properties that has not previously been reported for this material system under integrated tropical coastal exposure conditions.

Mechanically, the 5% replacement mix (MA-5) sustained a 28-day compressive strength of 31.4 MPa, satisfying SNI 2847:2019 requirements for marine exposure concrete, with no statistically significant reduction relative to the control. This mechanical adequacy is achieved not despite the microstructural changes induced by microalgae incorporation, but because of them: the densification of the interfacial transition zone through cell-wall fragment infilling and secondary C-S-H formation confirmed by SEM-EDS analysis and corresponding to an 11.2% reduction in porosity simultaneously explains the durability gains observed, including a 19.0% reduction in water absorption and a 20.8% reduction in chloride penetration depth. These results indicate that the pozzolanic and physical filler contributions of the microalgae cell wall, rather than acting merely as a cement diluent, actively participate in microstructural refinement at this replacement level, distinguishing MA-5 from higher-replacement mixes where the same organic content instead promotes agglomeration and mechanical weakening.

Beyond its structural performance, MA-5 concrete delivers a quantifiable climate mitigation benefit, sequestering a net 38.7 kg CO_2/m^3 a 15.8% reduction in embodied carbon relative to conventional concrete achieved through the combined pathways of biogenic carbon storage and enhanced mineral carbonation identified in this study. Taken together, these mechanical, durability, and carbon-sequestration outcomes establish that a 5% replacement level represents the optimal trade-off point in the system studied, beyond which the benefits of microalgae incorporation are outweighed by declining structural performance.

The principal scientific contribution of this study is the demonstration, for the first time within a single integrated experimental framework, that a dual-species microalgae blend can simultaneously improve durability and sequester carbon in concrete without compromising structural adequacy under the combined thermal, humidity, and chloride stressors representative of tropical coastal environments. This addresses a gap left unresolved by prior single-mechanism or single-species studies and provides an evidence base directly applicable to Indonesia's coastal green infrastructure programs, supporting the broader global effort to decarbonize the construction sector. Realizing this potential at scale will require further work on industrial-scale biomass cultivation consistency, long-term field durability, and economic feasibility, as outlined in the preceding discussion.

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