

Algae-Enhanced Sustainable Construction Mortar

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Abstract:

The present investigation evaluates the feasibility of developing sustainable cementitious mortar by partially replacing ordinary Portland cement with a ternary eco-additive system consisting of microalgae biomass, fly ash, and MEL furnace slag. The motivation behind this research arises from the urgent requirement to reduce carbon emissions associated with cement production while simultaneously valorizing industrial and biological waste streams. Microalgae biomass contains calcium, silica, and bio-organic compounds that can act as nucleation sites and internal curing agents, whereas fly ash and furnace slag exhibit well-known pozzolanic and latent hydraulic behavior. The combined action of these materials is expected to enhance mechanical performance and durability while lowering environmental impact.

Mortar mixes were prepared with varying replacement percentages (0–40%) of cement using algae powder, fly ash, and MEL furnace slag in different proportions. Fresh properties including flowability and water demand were assessed, followed by hardened properties such as compressive strength, flexural strength, density, and water absorption. Microstructural characteristics were interpreted based on hydration kinetics and bio-mineralization mechanisms. The study also evaluated durability behavior through sorptivity and permeability tests. Results demonstrated that the ternary system improves long-term strength and reduces pore connectivity due to secondary calcium silicate hydrate formation and bio-precipitation effects. The optimum performance was observed at 25–30% cement replacement where compressive strength exceeded the control mix after 28 and 56 days curing.

The study confirms that algae-based mortar can function not only as a structural material but also as a carbon-sequestering composite due to biological mineralization. Fly ash contributes to delayed hydration strength while MEL furnace slag enhances early-age reaction. The integrated effect produces dense microstructure and improved

durability characteristics. The research establishes the potential for producing low-carbon mortar suitable for masonry, plastering, and non-load-bearing structural components. This experimental investigation supports the development of circular construction materials and demonstrates a pathway for combining biological and industrial wastes into value-added construction products.

Keywords- Algae mortar, Fly ash, Furnace slag, Sustainable cement, Bio-mineralization, Green construction material, Pozzolanic reaction, Carbon sequestration

1. Introduction

1.1 Cement manufacturing contributes nearly eight percent of global carbon dioxide emissions and therefore sustainable alternatives are necessary in modern construction technology (Kumar & Singh, 2023). Supplementary cementitious materials such as fly ash and slag have been widely studied, but recent research has introduced biological additives including algae for eco-construction materials (Patel et al., 2023). Microalgae possess calcium carbonate forming capability and can act as a natural micro-reinforcement agent within cement matrix (Zhang et al., 2023).

1.2 Fly ash is a coal combustion by-product containing reactive silica and alumina that reacts with calcium hydroxide to produce secondary hydration products (Mehta & Roy, 2023). MEL furnace slag is a metallurgical waste rich in calcium and magnesium oxides that exhibits latent hydraulic properties (Sharma et al., 2023). Combining these with algae provides a hybrid mineral-biological reaction mechanism.

1.3 The novelty of this research lies in integrating bio-precipitation and pozzolanic reaction into a single mortar system. Previous investigations focused either on industrial waste or biomaterials independently (Das et al., 2023; Li et al., 2023). The present work explores the synergistic effect.

2. Materials and Experimental Program

2.1 Materials

Ordinary Portland cement (43 grade) was used as binder. River sand passing 2.36 mm sieve served as fine aggregate. Class F fly ash was collected from thermal power plant. MEL furnace slag was obtained from metallurgical industry. Microalgae biomass (dried powder) was cultured in nutrient medium and oven dried at 60°C.

Table 1: Mix Proportions of Mortar

Mix ID	Cement (%)	Fly Ash (%)	Slag (%)	Algae (%)	Water/Binder
M0	100	0	0	0	0.45
M1	85	10	3	2	0.45
M2	75	15	7	3	0.46
M3	70	18	8	4	0.47

M4	60	25	10	5	0.48
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2.2 Specimen Preparation

Mortar cubes of 70.6 mm were cast and cured in water for 7, 28, and 56 days. Prismatic specimens were prepared for flexural strength testing (Rao et al., 2023).

2.3 Testing Procedures

Flow table test determined workability (Ahmed et al., 2023). Compressive strength measured as per IS standards. Water absorption and sorptivity evaluated durability behavior (Chen et al., 2023).

3. Fresh and Mechanical Properties

3.1 Workability

Algae addition slightly increased water demand due to organic content. Fly ash improved flowability due to spherical particles, Slag improved cohesiveness.

3.2 Compressive Strength Strength increased gradually due to pozzolanic reaction and biological mineralization. M3 showed highest performance after 28 days.

Table 2: Mechanical Properties

Mix	7 Day Strength (MPa)	28 Day Strength (MPa)	56 Day Strength (MPa)	Water Absorption (%)
M0	24.5	32.0	34.2	6.8
M1	25.1	34.6	38.7	5.9
M2	26.3	36.8	41.5	5.2
M3	27.2	38.4	44.6	4.8
M4	23.8	35.1	40.2	5.0

3.3 Flexural Strength

Improvement due to micro-filler effect of algae cells acting as crack arresters.

4. Microstructural and Durability Characteristics

4.1 Hydration Mechanism

The hydration behavior of the developed mortar differs significantly from conventional cement mortar because the binder system does not depend solely on Portland cement clinker reactions. Instead, a coupled hydration–pozzolanic–biomineralization mechanism governs the formation of strength-bearing phases. Immediately after water addition, ordinary cement compounds such as tricalcium silicate (C₃S) and dicalcium silicate (C₂S) begin hydration producing calcium silicate hydrate (C-S-H) gel and calcium hydroxide. This primary reaction establishes the initial skeleton of the matrix. However, in the presence of fly ash, a secondary reaction becomes dominant at later ages. The amorphous silica and alumina present in fly ash consume calcium hydroxide and gradually produce secondary C-S-H gel, densifying the paste structure and reducing weak lime crystals (Roy et al., 2023).

MEL furnace slag contributes differently from fly ash. Because of its latent hydraulic nature and higher calcium content, slag participates earlier in hydration. Upon activation by alkaline pore solution generated from cement hydration, slag releases calcium and silica ions which rapidly nucleate additional hydration products. This leads to accelerated formation of calcium silicate hydrates during early curing stages and improves early strength development (Morales et al., 2023). Therefore, slag compensates for the delayed reaction characteristic of fly ash.

The most distinctive phenomenon in this research is the participation of algae biomass in mineral formation. The microalgae powder contains organic polysaccharides, proteins, and cell wall functional groups capable of binding calcium ions. During curing, these biological structures act as nucleation templates for calcium carbonate precipitation. Carbon dioxide dissolved in pore water reacts with calcium ions forming calcite crystals. This biomineralization fills microvoids and bridges microcracks within the cementitious matrix (Kaur et al., 2023). Unlike chemical carbonation that may weaken cement paste, this controlled bio-calcification strengthens the microstructure because precipitation occurs internally and gradually.

Thus, hydration progresses in three chronological stages: initial cement hydration forming primary C-S-H gel, slag-activated hydration enhancing early strength, and delayed pozzolanic reaction of fly ash combined with algae-induced calcite precipitation producing dense composite matrix. The coexistence of C-S-H gel and CaCO_3 crystals results in a hybrid inorganic–bio mineral structure characterized by reduced calcium hydroxide content and improved bonding between aggregate and paste.

4.2 Pore Structure

Pore refinement represents the primary reason behind the improved mechanical and durability properties of the developed mortar. Conventional cement mortar contains interconnected capillary pores generated from evaporation of mixing water and incomplete hydration. In the ternary blended system, several mechanisms operate simultaneously to reduce these pores.

First, the fine spherical particles of fly ash occupy voids between cement grains and act as micro-fillers, decreasing initial porosity. As hydration proceeds, secondary C-S-H gel forms within remaining spaces further blocking capillary channels (Santos et al., 2023). Second, furnace slag contributes additional hydration products that increase packing density, particularly during early curing when pores are most vulnerable to formation.

Third, algae particles function differently from mineral additives. The biological cell walls absorb water and behave as internal curing reservoirs. This prevents rapid moisture loss and promotes continuous hydration, leading to uniform gel formation. Additionally, calcite crystals precipitated by biomineralization physically plug microvoids. The combined effect converts large capillary pores into fine gel pores, significantly decreasing permeability.

Experimental observations showed that water absorption dropped by nearly thirty percent compared to the control mix. Reduced absorption indicates discontinuity in pore network rather than merely reduction in total void volume. A discontinuous pore system interrupts fluid transport pathways and improves long-term durability. Therefore, the improvement in density

is attributed not only to filler action but also to chemical transformation of hydration products and biological pore sealing.

4.3 Durability

Durability performance was evaluated through sorptivity and crack resistance behavior. Sorptivity measures the capillary suction of water into hardened mortar and directly reflects pore connectivity. The blended mortar exhibited markedly lower sorptivity values, confirming enhanced resistance to moisture ingress (Fernandez et al., 2023). This improvement results from the refined pore structure and formation of additional C-S-H gel that reduces permeability pathways.

Another notable durability improvement arises from bio-calcification. The algae-induced calcium carbonate precipitation occurs preferentially along microcracks where moisture and carbon dioxide concentration are higher. As calcite crystals grow, they seal the cracks and restore matrix continuity (Patel & Desai, 2023). This phenomenon can be considered a self-healing mechanism because it activates naturally without external treatment.

Furthermore, reduction in calcium hydroxide content due to pozzolanic reaction minimizes leaching and sulfate attack vulnerability. The dense microstructure also lowers chloride penetration risk, making the material suitable for humid or moderately aggressive environments. Overall, the ternary mortar system demonstrates improved resistance to moisture transport, chemical attack, and microcracking compared to conventional cement mortar.

5. Environmental and Sustainability Assessment

5.1 Carbon Reduction

One of the major environmental advantages of the developed material is reduction in carbon footprint. Cement manufacturing releases carbon dioxide through limestone calcination and fuel combustion. By replacing approximately thirty percent of cement with supplementary materials, clinker consumption decreases substantially. Calculations indicate that this replacement leads to nearly twenty-five percent reduction in CO₂ emissions per cubic meter of mortar (Banerjee et al., 2023). In addition, algae cultivation absorbs atmospheric carbon during photosynthesis, partially offsetting emissions associated with processing. Therefore, the binder system functions both as a low-carbon material and a carbon-capturing composite.

5.2 Waste Utilization

Fly ash and furnace slag are industrial by-products typically disposed in landfills or ash ponds. Their incorporation into mortar transforms waste into valuable construction resource and reduces environmental hazards such as soil and groundwater contamination (Khan et al., 2023). Algae biomass, often generated in wastewater treatment or biofuel production, also gains beneficial application instead of disposal. During growth, algae absorbs nutrients and carbon dioxide from environment, providing dual ecological benefit (Wang et al., 2023). Thus the developed mortar supports circular economy principles by linking industrial ecology and construction technology.

5.3 Life Cycle Perspective

A simplified life cycle assessment indicates lower embodied energy compared with ordinary mortar because production of supplementary materials requires minimal additional processing. Fly ash and slag are pre-existing industrial outputs, and algae drying consumes less energy than clinker production. Consequently, overall energy demand per unit strength decreases (Tripathi et al., 2023). When extended service life due to improved durability is considered, environmental benefits become even greater since repair and replacement frequency reduces.

6. Conclusion

The present experimental investigation demonstrates that the incorporation of microalgae biomass, fly ash, and MEL furnace slag as partial replacement of cement produces a highly efficient and sustainable mortar system. The material exhibits a multi-scale strengthening mechanism governed by primary cement hydration, secondary pozzolanic reaction of fly ash, latent hydraulic activity of slag, and biologically induced calcite precipitation from algae. These simultaneous processes significantly reduce calcium hydroxide content, refine pore structure, and form a dense composite matrix, ultimately improving both strength and durability characteristics. The optimum replacement level of approximately 25–30% cement provides superior compressive strength compared to conventional mortar while also reducing water absorption and permeability. Bio-calcification within the matrix contributes to microcrack sealing, indicating self-healing potential and long-term performance stability. From an environmental perspective, the ternary blend lowers carbon emissions, utilizes industrial waste materials, and introduces a carbon-sequestering biological component, thereby supporting circular construction practices. Overall, the developed mortar can be considered a viable eco-friendly alternative for masonry and plaster applications, combining structural adequacy with environmental sustainability and demonstrating significant promise for future green infrastructure development.

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