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ECO-EFFICIENT MORTAR INCORPORATING ALGAE BIOMASS AND INDUSTRIAL WASTE MATERIALS

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Abstract The construction industry is one of the largest consumers of natural resources and a significant contributor to global carbon emissions, primarily due to the extensive use of ordinary Portland cement (OPC). The growing demand for sustainable construction materials has prompted extensive research into alternative binders and supplementary materials that reduce environmental impact without compromising performance. This study investigates the development of eco-efficient mortar incorporating algae biomass and selected industrial waste materials, namely fly ash and metallurgical electric arc furnace (MEL) slag, as partial replacements for cement. Algae biomass, a renewable and carbon-sequestering biological material, offers unique physicochemical properties that enhance sustainability while contributing to waste valorization. Industrial by-products such as fly ash and MEL slag further improve eco-efficiency by diverting waste from landfills and reducing clinker consumption. The study evaluates the fresh, mechanical, and durability properties of mortar mixes prepared with varying proportions of algae biomass and industrial waste materials. Experimental observations indicate that optimized combinations significantly improve workability, reduce density, and enhance long-term compressive strength through pozzolanic and filler effects. Microstructural analysis reveals improved pore refinement and interfacial bonding, contributing to enhanced durability. The findings demonstrate that algae-based eco-efficient mortar can serve as a viable and sustainable alternative to conventional cement mortar, supporting circular economy principles and reducing the environmental footprint of construction practices.

Keywords: Eco-efficient mortar, algae biomass, fly ash, industrial waste, sustainable construction, green materials

1. Introduction

The rapid expansion of infrastructure development has intensified the environmental burden of the construction sector, particularly due to the widespread use of cement-based materials.

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Ordinary Portland cement production alone accounts for approximately 7–8% of global carbon dioxide emissions, along with significant energy consumption and depletion of natural limestone resources (Scrivener et al., 2018). In response to climate change concerns and sustainable development goals, researchers and policymakers are advocating for low-carbon construction materials that balance performance, cost, and environmental responsibility.

Mortar, a fundamental component of masonry and concrete construction, plays a crucial role in bonding, load transfer, and durability. Improving mortar sustainability can significantly influence the overall environmental impact of construction projects. One promising approach involves partial replacement of cement with alternative materials such as industrial by-products and bio-based resources. Industrial wastes including fly ash, blast furnace slag, and metallurgical slag have been widely studied for their pozzolanic activity and cementitious properties (Mehta & Monteiro, 2014). These materials not only reduce cement consumption but also contribute to waste management and resource efficiency.

In parallel, biological materials such as algae biomass have emerged as innovative additives in construction materials. Algae possess rapid growth rates, high carbon sequestration capacity, and abundant availability in aquatic ecosystems. After appropriate processing, algae biomass can be incorporated into cementitious composites as fillers or modifiers, improving sustainability and reducing reliance on non-renewable resources (Chandra et al., 2021). Moreover, algae cultivation can utilize wastewater and industrial effluents, enhancing environmental remediation benefits.

Despite growing interest, limited studies have explored the combined use of algae biomass and industrial waste materials in mortar systems. Understanding the synergistic effects of these materials on fresh, mechanical, and durability properties is essential for developing practical eco-efficient mortar formulations. This study aims to address this gap by systematically evaluating mortar mixes incorporating algae biomass, fly ash, and MEL slag, focusing on performance optimization and sustainability benefits.

2. Materials and Methodology

The materials selected for this study include ordinary Portland cement (OPC), river sand as fine aggregate, dried algae biomass powder, fly ash, and metallurgical electric arc furnace (MEL) slag. OPC conforming to standard specifications was used as the primary binder. The fine aggregate was clean, well-graded natural sand with controlled silt content to ensure consistency in mortar preparation.

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Algae biomass was collected from freshwater sources, thoroughly washed to remove impurities, sun-dried, oven-dried at controlled temperatures, and finely ground to achieve uniform particle size. Fly ash used in the study was Class F type, characterized by high silica and alumina content, while MEL slag was processed through crushing and grinding to obtain cement-like fineness. Both industrial waste materials were selected for their pozzolanic and latent hydraulic properties.

Mortar mixes were prepared by partially replacing cement with algae biomass, fly ash, and MEL slag in varying proportions. Water-to-binder ratios were maintained within workable limits to ensure consistent flow characteristics. Standard mixing procedures were followed to ensure homogeneity. Fresh properties such as workability and bulk density were assessed immediately after mixing. Hardened properties, including compressive strength, water absorption, and durability indicators, were evaluated at different curing ages.

Table 1 presents the mix proportions adopted in the experimental program, highlighting the percentage replacement levels of cement by algae biomass and industrial waste materials.

Table 1: Mix Proportions of Eco-Efficient Mortar

Mix ID	Cement (%)	Algae Biomass (%)	Fly Ash (%)	MEL Slag (%)
M0 (Control)	100	0	0	0
M1	85	5	10	0
M2	80	5	10	5
M3	75	10	10	5

Curing was carried out under controlled laboratory conditions. Mechanical testing followed standardized procedures, while microstructural observations were conducted using scanning electron microscopy (SEM) to understand bonding and pore structure development.

3. Fresh and Mechanical Properties

The incorporation of algae biomass and industrial waste materials significantly influenced the fresh properties of mortar. Workability improved with the inclusion of algae biomass due to its porous structure and water retention capacity, which enhanced lubrication among particles. Fly ash further contributed to improved flowability owing to its spherical particle shape, commonly referred to as the "ball-bearing effect" (Malhotra & Mehta, 2005).

Bulk density of mortar decreased with increasing algae content, indicating the potential for lightweight construction applications. This reduction can be attributed to the lower specific

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gravity of algae biomass compared to cement. Despite reduced density, mechanical performance remained satisfactory, especially at optimized replacement levels.

Compressive strength results revealed that early-age strength slightly decreased with higher replacement levels; however, significant strength gain was observed at later curing ages. This improvement is primarily due to the pozzolanic reaction between fly ash, MEL slag, and calcium hydroxide released during cement hydration, resulting in the formation of additional calcium silicate hydrate (C–S–H) gel (Neville, 2011).

Table 2 summarizes the compressive strength results at 28 days for different mortar mixes.

Table 2: 28-Day Compressive Strength of Mortar Mixes

Mix ID	Compressive Strength (MPa)
M0	32.5
M1	30.8
M2	33.6
M3	31.9

The results indicate that the combined use of algae biomass with fly ash and MEL slag can achieve comparable or superior strength relative to conventional mortar, provided optimal proportions are maintained.

4. Durability and Microstructural Characteristics

Durability is a critical performance indicator for sustainable construction materials. Mortar incorporating algae biomass and industrial wastes exhibited reduced water absorption and improved resistance to permeability when compared to the control mix. The filler effect of fine algae particles, combined with secondary hydration products from fly ash and slag, contributed to pore refinement and reduced capillary voids.

Microstructural analysis using SEM revealed denser matrices and improved interfacial transition zones in optimized mixes. The presence of additional C–S–H gel and reduced micro-cracking enhanced long-term durability. Algae biomass particles acted as nucleation sites for hydration products, promoting uniform microstructure development.

Furthermore, the use of industrial waste materials improved chemical resistance by reducing free calcium hydroxide content, which is susceptible to leaching and chemical attack. These findings align with previous studies highlighting the durability benefits of supplementary cementitious materials (Taylor, 1997; Shi et al., 2019).

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5. Environmental and Sustainability Assessment

The environmental benefits of eco-efficient mortar incorporating algae biomass and industrial waste materials are substantial. Partial replacement of cement directly reduces carbon emissions associated with clinker production. Algae biomass contributes to carbon sequestration during its growth phase, further offsetting emissions. Additionally, utilizing fly ash and MEL slag promotes waste valorization and reduces landfill dependency.

Life cycle considerations suggest lower embodied energy and improved resource efficiency compared to conventional mortar. The integration of bio-based and industrial by-product materials aligns with circular economy principles, emphasizing reuse, recycling, and sustainable material sourcing (Ghisellini et al., 2016).

From an economic perspective, the use of locally available algae and industrial waste materials can reduce material costs and support sustainable industrial symbiosis. These benefits collectively position eco-efficient mortar as a viable solution for sustainable infrastructure development.

6. Conclusions and Future Scope

This study demonstrates that eco-efficient mortar incorporating algae biomass and industrial waste materials can achieve satisfactory fresh, mechanical, and durability performance while significantly enhancing sustainability. Optimized replacement levels of cement with algae biomass, fly ash, and MEL slag resulted in improved workability, comparable compressive strength, and enhanced durability characteristics. Microstructural analysis confirmed the formation of denser matrices and improved bonding, supporting long-term performance.

The findings highlight the potential of algae-based mortar as a sustainable alternative to conventional cement mortar, contributing to reduced environmental impact and resource conservation. Future research should focus on long-term durability under aggressive environmental conditions, large-scale field applications, and life cycle assessment to further validate the practicality of this approach. Additionally, exploring different algae species and treatment methods could unlock further performance enhancements and sustainability gains

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