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Development of Eco-Friendly Lightweight Concrete

Mane Kalpesh Vasantrao*, S. P. Sharma[2] , L. S. Mahajan[3]

[1]*M.Tech Student, Department of Structural Engineering, Shreeyash College of Engineering & Technology, Chh. Sambhajinagar*
Email: manekalpesh01@gmail.com

[2,3]*Assistant Professor, Department of Structural Engineering, Shreeyash College of Engineering & Technology, Chh. Sambhajinagar*

**Corresponding author*

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Abstract

This study explores the development of sustainable concrete by partially replacing conventional cement with 10% fly ash cenosphere (FAC) and incorporating bacteria and calcium lactate as bio-based additives. The research evaluates the combined effects of these materials on the density and mechanical properties of concrete. Experimental results show that 10% FAC reduces concrete density by 4.62% after 28 days, contributing to the production of lightweight concrete. Although FAC alone decreases compressive, flexural, and tensile strengths, the addition of calcium lactate (0.015 mol/L) and bacteria significantly enhances these properties. The highest improvement in compressive strength (15%) and tensile strength (11%) is achieved with bacterial incorporation, while calcium lactate increases compressive, flexural, and tensile. The findings demonstrate that the combined use of FAC, bacteria, and calcium lactate effectively improves concrete performance, offering an environmentally friendly approach for producing lightweight, durable, and high-performance concrete for sustainable construction applications..

Keywords: Concrete, Compressive strength, Strength, RCA

1. Introduction

Concrete is the most extensively used construction material worldwide due to its excellent mechanical strength, durability, and versatility. However, the production of ordinary Portland cement (OPC), the primary binding material in concrete, contributes significantly to global carbon dioxide (CO_2) emissions and energy consumption. The cement industry accounts for approximately 7–8% of global anthropogenic CO_2 emissions, creating an urgent need for sustainable alternatives that reduce environmental impacts while maintaining structural performance [1,2].

One of the most effective strategies for developing sustainable concrete is the utilization of industrial by-products as supplementary cementitious materials. Fly ash, a residue generated from coal-fired thermal power plants, has been widely used in concrete because of its pozzolanic properties, improved durability, and reduced environmental footprint. Among the various components of fly ash, fly ash cenospheres (FAC) are lightweight, hollow, spherical particles possessing low density, high strength, excellent thermal insulation, and good chemical stability. These unique characteristics make FAC an attractive material for producing lightweight concrete while promoting the beneficial utilization of industrial waste [3,4].

The incorporation of fly ash cenospheres into cementitious composites can significantly reduce the density of concrete, making it suitable for lightweight structural and non-structural applications. Nevertheless, excessive replacement of cement with FAC may reduce compressive, tensile, and flexural strengths because of its hollow structure and lower cementitious reactivity compared with Portland cement. Therefore, additional approaches are required to compensate for the loss in mechanical performance while preserving the sustainability benefits offered by FAC incorporation [4,5].

In recent years, bio-concrete has emerged as an innovative and environmentally friendly technology for enhancing the durability and service life of concrete. This technology is based on Microbially Induced Calcium Carbonate Precipitation (MICP), in which bacteria precipitate calcium carbonate ($CaCO_3$) within pores and microcracks. The deposited calcite crystals densify the cement matrix, reduce permeability, improve crack resistance, and enhance the mechanical properties of concrete. Several bacterial species, particularly Bacillus species, have demonstrated excellent survivability in the highly alkaline concrete environment and have been successfully used for self-healing and strength enhancement applications [6–8].

The efficiency of bacterial biomineralization depends greatly on the availability of a suitable calcium source and nutrient supply. Calcium lactate has been widely investigated as an effective nutrient because it provides a readily available carbon source for bacterial metabolism, facilitating calcium carbonate precipitation. During bacterial metabolic activity, calcium lactate is converted into calcium carbonate crystals that fill pores and microcracks, resulting in improved compressive strength, reduced water permeability, and enhanced durability. Previous studies have shown that bacterial concrete incorporating calcium lactate exhibits superior mechanical performance and crack-healing capability compared with conventional concrete [9].

Recent investigations have also highlighted the synergistic benefits of combining fly ash with bacterial biomineralization. Fly ash not only serves as a sustainable cement replacement but also provides a favorable environment for bacterial survival and calcite precipitation. The interaction between bacterial activity and fly ash contributes to pore refinement, enhanced matrix densification, and improved long-term durability. Despite these advancements, studies specifically investigating the combined influence of fly ash cenospheres, bacteria, and calcium lactate on the mechanical properties of lightweight concrete remain limited [5,8].

Therefore, the present study aims to investigate the mechanical performance of sustainable concrete incorporating fly ash cenosphere as a partial replacement for cement together with bacteria and calcium lactate. The study evaluates the effects of these materials on concrete density, compressive strength, flexural strength, and split tensile strength. The proposed approach seeks to overcome the reduction in strength associated with FAC while producing lightweight, durable, and environmentally sustainable concrete suitable for modern construction applications.

2. Literature Review

The increasing demand for sustainable construction materials has accelerated research on supplementary cementitious materials (SCMs) and bio-based technologies to improve the performance and durability of concrete. Among the available SCMs, fly ash has gained considerable attention because of its pozzolanic characteristics, ability to reduce cement consumption, and contribution to long-term strength development. The use of fly ash also minimizes industrial waste disposal while lowering the carbon footprint associated with cement production [11].

Fly ash cenospheres (FAC), a lightweight fraction of fly ash, possess hollow spherical morphology, low density, and high thermal stability. Their incorporation into concrete reduces the self-weight of structural members and improves thermal insulation. However, increasing FAC content generally decreases compressive, tensile, and flexural strengths due to reduced matrix density and weaker interfacial bonding between the cement paste and lightweight particles. Consequently, researchers have focused on combining FAC with strength-enhancing materials to compensate for these reductions [12].

Microbial-induced calcium carbonate precipitation (MICP) has emerged as one of the most promising bio-based techniques for improving concrete durability. In this process, bacterial metabolic activity produces calcium carbonate crystals that fill pores and seal microcracks, thereby enhancing strength and reducing permeability. Various bacterial species, particularly those belonging to the Bacillus genus, are capable of surviving the highly alkaline environment of concrete and producing substantial amounts of calcite precipitation [13].

Several studies have demonstrated that bacterial concrete exhibits higher compressive strength than conventional concrete because bacterial calcium carbonate fills internal voids and refines the pore structure. Besides improving mechanical properties, bacterial concrete significantly reduces water absorption, chloride penetration, and crack propagation, thereby extending the service life of reinforced concrete structures exposed to aggressive environments [14].

The effectiveness of bacterial concrete depends on the availability of nutrients and calcium sources required for microbial metabolism. Calcium lactate has been identified as an efficient nutrient because it supports bacterial growth while providing calcium ions necessary for biomineralization. During the bacterial metabolic process, calcium lactate is converted into calcium carbonate, which enhances matrix densification and improves both strength and durability. Studies have reported significant improvements in crack healing and mechanical performance when calcium lactate is incorporated into bacterial concrete mixtures [15].

Researchers have also investigated the influence of bacteria on the microstructure of cementitious materials using scanning electron microscopy (SEM), X-ray diffraction (XRD), and energy-dispersive spectroscopy (EDS). These investigations confirmed the formation of calcite crystals within pores and microcracks, resulting in reduced porosity and enhanced interfacial bonding between hydration products and aggregates. Such microstructural improvements are directly responsible for the observed increase in compressive, tensile, and flexural strengths [16].

In addition to bacterial mineralization, several investigations have evaluated the combined utilization of industrial by-products and microbial technology. The incorporation of fly ash creates a finer pore structure and provides additional nucleation sites for calcium carbonate precipitation. This synergistic interaction improves the hydration process and contributes to better long-term durability compared with conventional concrete [17].

Lightweight concrete prepared using fly ash cenospheres has also been investigated for structural and insulation applications. Researchers have reported that optimum replacement levels of FAC provide satisfactory mechanical performance while significantly reducing concrete density. However, excessive replacement levels lead to increased porosity and lower strength, indicating the importance of identifying an optimum FAC content for practical applications [18].

Recent studies have emphasized the importance of sustainable bio-concrete in reducing maintenance costs and increasing the service life of infrastructure. Self-healing concrete containing bacteria can autonomously repair microcracks before they propagate into major structural defects, thereby reducing repair requirements and improving the lifecycle performance of concrete structures. This technology is considered one of the most promising approaches for future smart and sustainable infrastructure [19].

Although significant progress has been made in the fields of lightweight concrete, bacterial concrete, and supplementary cementitious materials, limited research has investigated the combined effects of fly ash cenospheres, bacteria, and calcium lactate in a single concrete system. Therefore, the present study aims to evaluate the synergistic influence of these materials on density, compressive strength, flexural strength, and split tensile strength to develop lightweight, durable, and environmentally sustainable concrete suitable for modern construction applications [20].

3. Materials and Method

Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269:2013 was used as the primary binding material in this investigation. The cement possessed adequate fineness, normal consistency, and strength characteristics suitable for producing structural concrete. River sand conforming to Zone II of IS 383:2016 was used as the fine aggregate because of its clean surface texture, proper grading, and low impurity content. Crushed granite coarse aggregate with a nominal maximum size of 20 mm was selected as the coarse aggregate to ensure good strength and workability. Potable water free from harmful salts and organic impurities was used for both concrete mixing and curing in accordance with IS 456:2000.

Fly ash cenosphere (FAC), a lightweight hollow aluminosilicate material recovered from fly ash generated by thermal power plants, was employed as a partial replacement for cement. The cenospheres possess low density, spherical morphology, excellent thermal insulation, and good chemical stability, making them suitable for producing lightweight concrete. In the present study, fly ash cenosphere was incorporated at an optimum replacement level of 10% by weight of cement. Although the incorporation of FAC reduces the density of concrete, it may also decrease mechanical strength because of its hollow structure and relatively lower pozzolanic activity compared with ordinary Portland cement.

A bacterial culture belonging to the Bacillus genus was incorporated into the concrete mixtures due to its ability to survive the highly alkaline environment of cementitious materials and precipitate calcium carbonate through microbial-induced calcium carbonate precipitation (MICP). The bacterial suspension was prepared under controlled laboratory conditions to obtain the desired cell concentration before mixing. Calcium lactate was used as a bacterial nutrient and calcium source at a concentration of 0.015 mol/L. During bacterial metabolism, calcium lactate facilitates the formation of calcium carbonate crystals, which fill pores and microcracks, thereby improving the microstructure, mechanical strength, and durability of concrete.

The experimental investigation was carried out to evaluate the influence of fly ash cenosphere, bacteria, and calcium lactate on the mechanical performance of concrete. Initially, a conventional concrete mix was designed in accordance with IS 10262:2019 to achieve the desired strength. A control mix containing only ordinary Portland cement was prepared and used as the reference specimen. Subsequently, cement was partially replaced with 10% fly ash cenosphere to produce lightweight concrete. Additional concrete mixtures were prepared by incorporating calcium lactate at a concentration of 0.015 mol/L and bacterial culture individually and in combination with the fly ash cenosphere mixture to evaluate their synergistic effects.

The dry constituents, including cement, fly ash cenosphere, fine aggregate, and coarse aggregate, were thoroughly mixed until a uniform blend was obtained. Water containing the required quantity of bacterial suspension and calcium lactate solution was then gradually added to the dry mixture while continuous mixing was maintained to ensure homogeneous distribution of all constituents throughout the concrete. Fresh concrete was placed into clean and properly oiled moulds in three equal layers, with each layer compacted using a table vibrator to eliminate entrapped air and obtain dense specimens. After casting, the specimens were covered to prevent moisture loss and demoulded after 24 hours.

The demoulded specimens were cured in clean water at room temperature for 28 days to facilitate complete cement hydration and bacterial mineralization. At the end of the curing period, the density of hardened concrete was determined, followed by mechanical testing. Compressive strength was evaluated using cube specimens in accordance with IS 516 (Part 1):2021, while flexural strength was determined using prism specimens subjected to two-point loading. Split tensile strength was measured using cylindrical specimens under diametral compression. The experimental results obtained from the modified concrete mixtures were compared with those of the control concrete to assess the effectiveness of fly ash cenosphere, bacteria, and calcium lactate in improving the strength and reducing the density of concrete. The observed results were analyzed to identify the optimum combination capable of producing lightweight, durable, and environmentally sustainable concrete suitable for structural applications.

4. Result

The split tensile strength results reveal that the incorporation of fly ash cenosphere alone led to a gradual reduction in the tensile performance of concrete as the replacement level increased. This behavior can be attributed to the hollow morphology and lower cementitious reactivity of fly ash cenospheres, which increase the porosity of the cement matrix and weaken the bond between the paste and aggregate. Consequently, the tensile resistance of the concrete decreased with higher FAC content.

The incorporation of calcium lactate effectively mitigated the reduction in tensile strength caused by fly ash cenosphere. Among the dosages investigated, the intermediate calcium lactate concentration demonstrated the most favorable performance, indicating that an optimum nutrient level promotes efficient calcium carbonate precipitation and improves the densification of the cementitious matrix. The enhanced microstructure contributed to better crack resistance and stronger interfacial bonding, resulting in improved tensile behavior.

The combined use of bacteria and calcium lactate produced the most significant enhancement in split tensile strength throughout the study. The bacterial activity facilitated microbial-induced calcium carbonate precipitation, which filled internal pores and microcracks, reduced matrix porosity, and strengthened the interfacial transition zone. This biomineralization process resulted in a denser and more homogeneous concrete microstructure, thereby improving its resistance to tensile stresses.

Overall, the findings demonstrate that although fly ash cenosphere alone tends to reduce the tensile capacity of concrete, the simultaneous incorporation of bacteria and calcium lactate effectively compensates for this limitation. The synergistic interaction between these constituents enhances matrix densification and crack-bridging capability, leading to improved tensile performance while maintaining the sustainability benefits associated with the use of fly ash cenosphere. These results confirm that bio-modified FAC concrete is a promising alternative for the development of lightweight, durable, and environmentally sustainable construction materials.

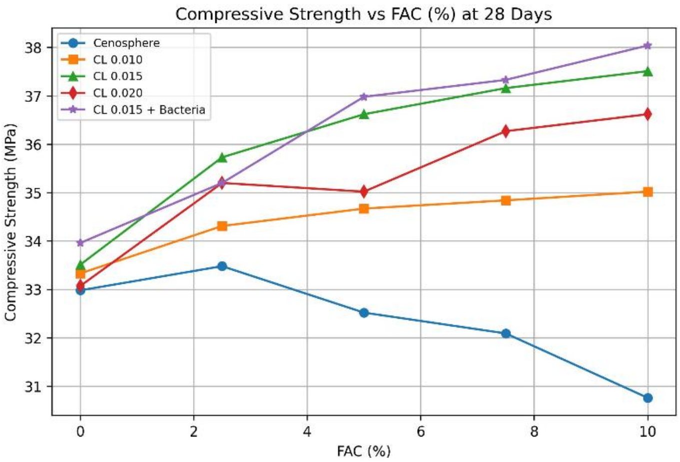

Fig. 1 - Compressive Strength

5. Conclusion

This study demonstrated that the incorporation of fly ash cenosphere (FAC) can produce lightweight and sustainable concrete; however, its use alone leads to a reduction in mechanical strength. The addition of calcium lactate and bacterial culture effectively compensated for this loss by enhancing the concrete microstructure through microbial-induced calcium carbonate precipitation. Among the mixtures investigated, the combination of FAC, calcium lactate, and bacteria exhibited the best overall mechanical performance, indicating a strong synergistic effect. The results confirm that bio-modified FAC concrete is a promising and eco-friendly construction material capable of achieving improved strength while reducing concrete density. Therefore, the proposed approach offers a sustainable solution for developing durable, lightweight, and high-performance concrete suitable for future infrastructure applications.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

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