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INVESTIGATION OF FLY ASH POLYMER COMPOSITES FOR ENHANCED CONSTRUCTION APPLICATIONS

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ABSTRACT

This study explores the development of a sustainable fly ash (FA) and cold-setting resin composite with enhanced mechanical properties, designed specifically for construction applications where durability and environmental impact are key considerations. As fly ash is a byproduct of thermal power plants and widely available at low cost, its utilization addresses both economic and environmental issues associated with its disposal. However, fly ash in its raw form often lacks the necessary mechanical strength for direct application in construction. By incorporating a cold-setting resin, this study aims to overcome these limitations, leveraging FA as a primary component in a high-performance composite material.

The study involved creating various compositions of FA and resin, with FA proportions ranging from 75% to 85% by weight, to determine the optimal balance for achieving maximum compressive strength, hardness, water resistance, and thermal insulation. Each composite was carefully tested for its physical and thermal properties, simulating the conditions required for construction materials. Results demonstrated that an FA composition of 85 wt.% achieved the highest compressive strength and hardness values, along with improved density and moderate water absorption. These qualities suggest that FA-resin composites could perform well as load-bearing materials in both structural and insulation applications.

To gain a deeper understanding of the composite's structural characteristics, microstructural analyses were conducted using scanning electron microscopy (SEM), X-ray diffraction (XRD), and Fourier transform infrared spectroscopy (FTIR). SEM imaging revealed uniform particle distribution and bonding within the composite, with minimal voids and fractures, which are essential for structural integrity. XRD analysis identified the presence of calcium silicate hydrate (CSH) and calcium aluminate silicate hydrate (CASH) phases in the cured samples, phases known to enhance the mechanical strength and durability of cementitious materials. FTIR provided insight into the chemical bonds within the composite, especially the formation of stable Si-O and Al-O bonds, which further contribute to the material's durability and thermal resistance.

The findings indicate that incorporating FA as the primary component in construction materials can significantly reduce reliance on traditional clay and other natural resources, making FA-resin composites a viable eco-friendly alternative. Additionally, the low thermal conductivity of these composites makes them suitable for use in insulation, contributing to energy efficiency in buildings. By developing a composite that not only meets the mechanical demands of construction but also provides environmental benefits, this study highlights the potential of fly ash composites to advance sustainable building practices.

Keywords: Fly Ash (FA), Cold-Setting Resin, Composite Materials, Mechanical Properties, Sustainable Construction, Environmental Impact, Compressive Strength, Hardness, Water Resistance, Thermal Insulation, Microstructural Analysis, Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), Calcium Silicate Hydrate (CSH), Calcium Aluminate Silicate Hydrate (CASH), Eco-Friendly Materials, Energy Efficiency, Structural Integrity, Material Durability

I. INTRODUCTION

Fly ash, an abundant byproduct of coal combustion in thermal power plants, presents both opportunities and challenges for construction applications. It is widely regarded as a low-cost material that can be repurposed, offering a sustainable solution to reduce waste from power generation. However, due to its relatively low inherent strength and other limitations, raw fly ash cannot be used directly in load-bearing structures or other high-strength applications without modification. To address this, recent research has explored methods to enhance the mechanical and thermal properties of fly ash through composite formulations, thus expanding its range of potential applications in eco-friendly construction. The current study focuses on developing a composite material in which fly ash is reinforced with a cold-setting resin binder. Cold-setting resins are particularly advantageous for such applications, as they cure at ambient temperatures without requiring additional heat, which makes them energy-efficient and suitable for large-scale production. By binding the fly ash particles together, the resin provides structural integrity, increased compressive strength, and enhanced durability, allowing the material to meet construction-grade performance standards. This approach seeks not only to capitalize on the availability and low cost of fly ash but also to create a material that supports sustainable building practices by reducing the demand for conventional resources like cement and clay. The study's primary objective is to evaluate how varying the ratio of fly ash to resin influences the composite's mechanical and thermal properties. Three distinct FA-to-resin weight ratios—75:25, 80:20, and 85:15—were prepared and tested to determine the optimal formulation for construction purposes. Key properties such as compressive strength, hardness, water absorption, and thermal conductivity were measured, as these directly impact a material's suitability for structural applications. Higher fly ash content was hypothesized to increase compressive strength and hardness, providing a durable matrix when adequately bonded with resin. Additionally, the thermal conductivity of the composite was assessed to evaluate its potential as an insulating material, which could further support its use in energy-efficient buildings. To complement these property assessments, advanced microstructural analyses were conducted using Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD). SEM imaging provided insights into the distribution and bonding of fly ash particles within the composite matrix, revealing the effectiveness of the resin in achieving a cohesive structure. A tightly bonded matrix with minimal voids or weak points would signify a more durable composite material. XRD analysis allowed for identification of key crystalline phases, such as calcium silicate hydrate (CSH) and calcium aluminate silicate hydrate (CASH), which are typically formed in cementitious materials and contribute to enhanced hardness and durability. By understanding the microstructural changes induced by varying the FA-to-resin ratio, the study aimed to establish the correlation between the composite's internal structure and its mechanical performance. In summary, this research represents a step toward developing a fly ash-based composite material that is both economically and environmentally viable. Through careful analysis of different FA-to-resin ratios and their impact on mechanical and thermal properties, the study seeks to create a durable, sustainable alternative to conventional building materials. The findings could pave the way for broader adoption of fly ash composites in construction, aligning with global efforts to minimize waste, reduce carbon emissions, and support the transition to eco-friendly building practices.

II. METHODOLOGY

In this study, the fly ash used was sourced from a local thermal power plant, chosen for its consistency and availability as a waste byproduct of coal combustion. Before testing, the fly ash was carefully prepared to ensure uniformity and reliability in experimentation. The ash was oven-dried at temperatures ranging from 110°C to 160°C to remove any residual moisture that could interfere with the binding process and affect the composite's mechanical properties. This drying step also enhanced the fly ash's compatibility with the resin, ensuring better particle integration and overall stability in the final composite.

To bind the fly ash particles, a cold-setting resin and its corresponding hardener were selected as the binding agents. Cold-setting resins cure at room temperature without requiring additional heating, which makes them ideal for energy-efficient, large-scale production. These resins also provide a strong, durable matrix for the fly ash particles, helping to overcome the material's natural brittleness and increasing the composite's overall structural integrity. The hardener, used as an accelerator, initiated the polymerization process in the resin, allowing for rapid setting and improved cohesion within the composite.

Sample Preparation

To test the effects of varying fly ash-to-resin ratios on the composite's properties, samples were prepared in three specific compositions: 75% fly ash with 25% resin, 80% fly ash with 20% resin, and 85% fly ash with

15% resin. These weight ratios were chosen to identify the optimal balance between fly ash content and binding material, aiming to achieve the highest possible strength and durability. Each mixture was thoroughly homogenized using a mechanical vibrator to ensure even distribution of the resin and fly ash particles. This step is crucial in composite preparation as it minimizes the formation of weak points or inconsistencies within the samples, which could otherwise compromise the material's performance under stress.

After homogenization, the mixtures were compacted into cylindrical samples. Cylindrical molds of uniform size were used to standardize the shape and dimensions of the samples, allowing for consistent testing and comparability between different compositions. The samples were compacted under controlled pressure to achieve maximum density and eliminate air pockets, further enhancing their mechanical properties. Following compaction, the samples were left to cure at room temperature, allowing the cold-setting resin to harden and form a strong, cohesive bond between the fly ash particles.

Testing Procedures

Once prepared, the composite samples underwent a series of tests to evaluate their mechanical, thermal, and microstructural properties. These tests were designed to assess the material's suitability for construction applications and to determine how the varying fly ash-to-resin ratios influenced performance.

Mechanical Properties: The hardness of each sample was measured using a Vickers hardness tester, which applies a standardized load to determine the material's resistance to deformation. This metric is essential for construction materials, as higher hardness typically correlates with better wear resistance. Compressive strength tests were conducted according to industry standards to measure the samples' ability to withstand axial loads. Compressive strength is a critical factor in construction, as it indicates how well a material can support weight without failing.

Water Absorption and Density: To evaluate the composite's resistance to moisture and its density, the samples were first dried and weighed to establish a baseline. They were then submerged in water for a specified period to measure water absorption rates. Following water treatment, the samples were weighed again to determine the percentage of water absorbed. Density measurements were calculated both before and after water absorption testing, providing insights into the composite's porosity and potential changes in structure when exposed to moisture.

Thermal Conductivity: Thermal conductivity, a measure of a material's ability to transfer heat, is particularly relevant for construction materials used in energy-efficient buildings. The KD2 Pro Analyzer was used to measure thermal conductivity, following ASTM standards. This handheld device includes various sensors that can be inserted into the material to capture precise thermal data. Lower thermal conductivity values are desirable in construction materials intended for insulation, as they indicate better resistance to heat transfer.

Microstructural Analysis: To understand the internal structure and bonding characteristics of the fly ash-resin composites, microstructural analyses were conducted using Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD). SEM provided high-resolution images of the composite's surface, revealing details about particle distribution, bonding, and the presence of voids or cracks. Uniform particle distribution and strong inter-particle bonding are indicators of a well-formed composite material. XRD analysis identified the crystalline phases present within the samples, particularly focusing on compounds like calcium silicate hydrate (CSH) and calcium aluminate silicate hydrate (CASH). These phases are known to improve mechanical properties in cementitious materials and contribute to the composite's durability and strength.

This comprehensive testing approach allowed for a thorough evaluation of each sample's performance, providing insights into how different compositions of fly ash and resin affect the final composite's suitability for structural applications. Through these tests, the study aimed to identify the optimal fly ash-to-resin ratio for a strong, durable, and environmentally friendly construction material.

III. RESULTS AND DISCUSSION

The experimental testing provided valuable insights into the mechanical, thermal, and physical properties of fly ash (FA) and resin composites, highlighting how varying FA-to-resin ratios impact performance. Overall, higher fly ash content consistently improved certain properties, making the composite more suitable for structural applications while maintaining low thermal conductivity for insulation. Below is an expanded analysis of the specific results for each tested property:

Compressive Strength: The compressive strength of the composites was found to increase with a higher proportion of FA, reaching a peak value of 11.28 MPa for samples with 85% FA content in dry conditions. This improvement in strength can be attributed to the increased inter-particle bonding provided by the higher concentration of FA, which creates a more cohesive and robust matrix when combined with the resin. Lower FA compositions, such as 75% FA with 25% resin, exhibited comparatively lower compressive strength, indicating that a higher resin content may not contribute significantly to structural strength and may act mainly as a binder. The optimal composition at 85% FA suggests that the composite can withstand higher axial loads, making it suitable for use in load-bearing applications within construction.

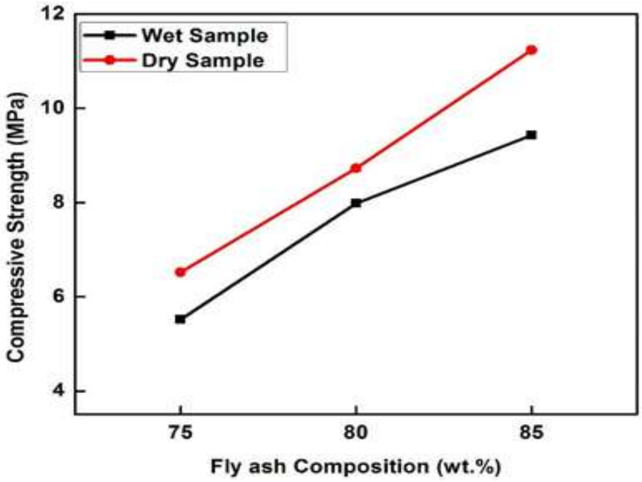

Figure 1: Compressive Strength of Compacts at different FA compositions

Hardness: Hardness testing, conducted using the Vickers hardness method, revealed a range of values from 32.93 HV to 47.37 HV. As with compressive strength, the highest hardness value was recorded in samples with 85% FA, suggesting that the increased fly ash content contributes to better resistance against surface deformation. This increased hardness likely stems from the presence of calcium silicate hydrate (CSH) and calcium aluminate silicate hydrate (CASH) phases, as identified in the microstructural analysis. These phases improve the material's internal cohesion, resulting in a composite that is less prone to wear and better suited for environments that require durable surface resistance.

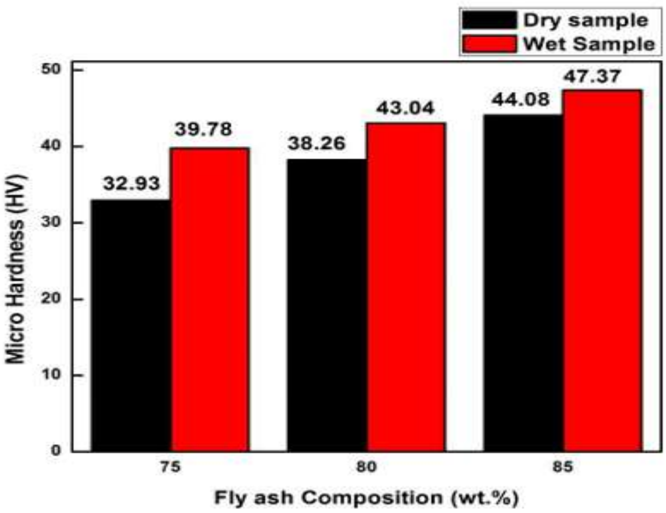

Figure 2: Variation in hardness values with wt. % of FA

Water Absorption and Density: The water absorption capacity and density of the composites were assessed to gauge their potential longevity and suitability for moisture-prone environments. The highest FA composition (85%) showed a water absorption rate of 19.09% after immersion in water. Although this absorption rate is relatively high, it remains within acceptable limits for construction applications in developing countries, where standards typically allow up to 20% water absorption for certain building materials. The density of the composites also varied with FA content, showing an increase post-water treatment due to the filling of pores through capillary action. In dry conditions, the density of the 85% FA composite reached approximately 1.35 g/cm^3, while post-treatment density rose to 1.67 g/cm^3, indicating that the material becomes denser and potentially stronger upon exposure to moisture.

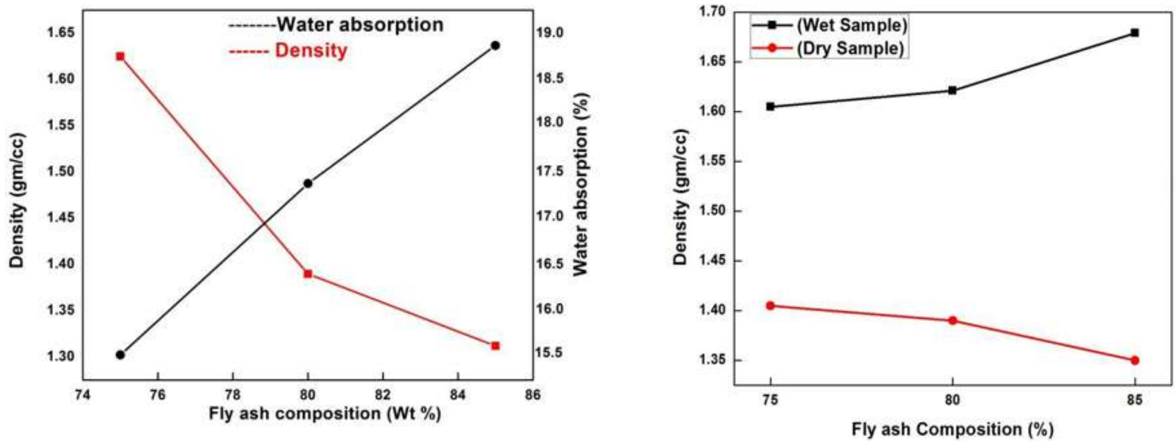

Figure 3: Water absorption and density as a function of FA Composition

Thermal Conductivity: Thermal conductivity, an important parameter for materials used in energy-efficient buildings, was measured to evaluate the composite's insulation potential. The results indicated a reduction in thermal conductivity as FA content increased, with the 85% FA composite demonstrating the lowest thermal conductivity value among all tested compositions. This reduction suggests that FA-resin composites with higher FA content are less effective at conducting heat, making them suitable for insulation applications. Compared to traditional clay-based materials with thermal conductivity values around 0.82 W/mK, the FA composites achieved values closer to 0.055 W/mK, reflecting superior insulating characteristics. This property positions FA composites as promising candidates for energy-efficient wall and insulation materials in building construction.

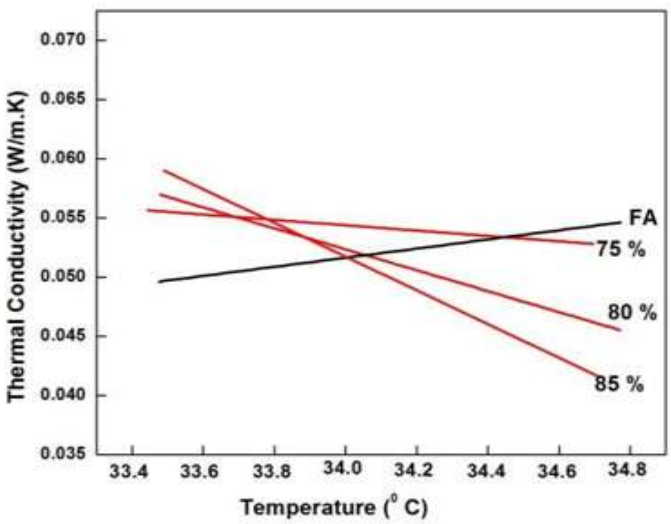

Figure 4: Thermal conductivity of FA –Resin powder Mix at different compositions

In summary, the composite with 85% FA content demonstrated optimal performance across multiple parameters, including compressive strength, hardness, density, and thermal insulation. These results underscore the potential of FA-resin composites as eco-friendly construction materials, providing both strength and energy efficiency benefits. The study's findings suggest that increasing FA content enhances the composite's structural integrity and thermal performance, making it a viable alternative to conventional materials in sustainable construction.

IV. CONCLUSION

The findings indicate that increasing FA content in the composite enhances hardness and compressive strength due to improved particle bonding, confirmed through SEM. However, excess resin reduced compressive strength, underscoring its role as a binding agent rather than a structural component. XRD analysis also revealed the presence of CSH and CASH phases, which contribute to hardness and thermal insulation properties, making the composite suitable for building applications. The FA-resin composite developed in this study offers a sustainable alternative to conventional bricks, with superior mechanical strength and insulating properties. The increased use of FA not only reduces environmental waste but also diminishes clay consumption. This composite is therefore recommended for eco-friendly construction.

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