Fly Ash Polymer Composites Enhancing Pore Refinement and Sulphate Resistance in Cement

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Abstract- Fly ash has also become quite renowned as an important by-product material from the combustion of coal; it finds various applications as an additive to both polymer composites and cementitious systems, primarily enhancing their mechanical properties including compressive strength, wear resistance, and resistance against sulphate penetration as well as reduced porosity resulting from pozzolanic reactions. This review focuses on the synthesis, characterization, and diversified applications of fly ash polymer composites, which include pore refinement and long-term stability. Advanced analytical techniques, such as scanning electron microscopy (SEM), X-ray diffraction (XRD), and thermogravimetric analysis (TGA), are essential in understanding the microstructure and hydration mechanisms of these composites. The use of fly ash in cement not only reduces CO_2 emissions but also helps in the development of sustainable infrastructure by reusing industrial waste. This would imply the removal of all such major issues found in conventional cementitious systems such as brittleness, permeability, and high maintenance costs by modern advances in polymer-modified concretes and hybrid materials. From structural components to sewage systems, or repair works, fly ash polymer composites constitute an environment-friendly, high-performance alternative with all its prospects resonating well within global aspirations of sustainability and resilience for construction.

Keywords- Fly ash, Polymer composites, Pore refinement, Sulphate resistance, Cementitious systems, Sustainability, Mechanical properties, Analytical techniques

I. INTRODUCTION

Fly ash is a coal combustion by-product in thermal power plants. It acts as a filler and binder in materials, thereby enhancing the mechanical, thermal, and wear-resistant properties of the materials. In aluminium alloys and polymer composites, fly ash improves the structure, bonding strength, and wear resistance. Such materials can be used in durable and cost-effective applications, especially in the automotive industry [1]. Fly ash composites present better hardness, stiffness, and machinability properties with further benefits when materials like boron carbide are added. Global utilization of fly ash is very low, as only 25–30% is reused; the rest of it is a waste in landfills, ponds, and slag piles, causing environmental and financial challenges. Research emphasizes the use of fly ash in an efficient manner, especially in construction, in order to prevent these problems and encourage sustainable development [2], [3].

Fly ash is siliceous and aluminous in character with a large concentration of silicon dioxide, aluminium oxide, and iron oxide, accompanied by high surface area and very low bulk density. The Class C and Class F fly ash types are characterized as Class C is cementitious in nature with higher lime contents and Class F primarily pozzolanic in character. Fly ash has been effectively utilized to replace ordinary Portland cement (OPC) in concrete and reduce carbon emissions and deal with FA waste [4]. Since cement production is a primary source of CO2 emission, replacing OPC with fly ash presents a great opportunity for sustainable infrastructure development while reducing virgin resources usage and minimizing environmental pollution [5].

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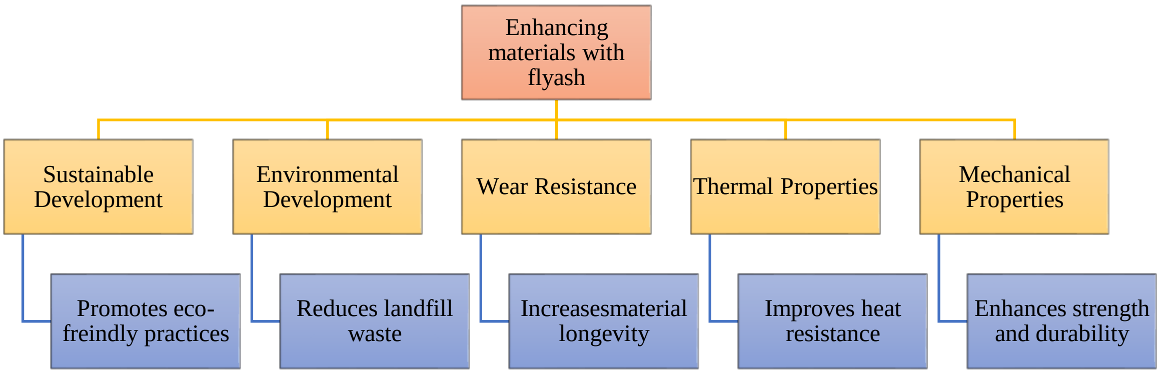

Fig.1: Enhancing Material with Flyash

This Fig.1 depicts the multiplicity of benefits that fly ash brings in material property improvement. It centers at "Improving materials with fly ash" and expands into five main categories: Sustainable Development, Environmental Development, Wear Resistance, Thermal Properties, and Mechanical Properties. All of these are further detailed with specific benefits. For example, fly ash encourages environmental-friendly practices in sustainable development, reduces landfill waste in environmental development, and enhances material life through improved wear resistance. It also improves heat resistance under thermal properties and strengthens materials for more durability under mechanical properties. This diagram briefly describes the wide range of applications and benefits of using fly ash in different material systems.

The PCCs containing fly ash are a new advanced material for modern infrastructures. In these composites, the polymer types such as thermosetting, thermoplastic, and elastomers act synergistically with the cement matrix, thereby improving adhesion, permeability, and resistance to chemical attacks. Developments in polymer-modified concretes and polymer-impregnated concretes have led to its use in applications such as sewage systems, flooring, and structural repair [6], [7]. Advances in atomistic modeling and polymer-based admixtures have further optimized mix designs, reducing costs and improving durability. Hybrid materials that incorporate fly ash and polymers have been developed to address challenges such as brittleness, porosity, and long-term maintenance costs in conventional concrete [8].

The addition of fly ash and polymer composites addresses critical pore refinement and sulphate resistance concerns, which are crucial for maintaining the long-term performance of cement in aggressive environments. Large pore structures in traditional cement allow for the ingress of harmful ions and chemical deterioration. The addition of fly ash and polymers creates a dense microstructure that provides high durability and chemical resistance to the infrastructure with improved lifecycle performance. This review points out the need for such materials in achieving sustainable and resilient construction practices, where such materials could be used to reduce costs and environmental impacts while enhancing structural longevity [9].

II. MECHANISMS OF PORE REFINEMENT IN FLY ASH POLYMER COMPOSITES

Fly ash is also an important constituent in reducing porosity through pozzolanic reaction with calcium hydroxide in cement. Secondary calcium silicate hydrates, C-S-H, are produced, which fill the voids in the matrix, thus resulting in a denser microstructure. Fly ash particles also act as micro-fillers, occupying spaces in the cement matrix physically and further minimizing porosity. Pore refinement improves the mechanical strength and limits the ingress of harmful ions and moisture [10]. Polymers in the composite chemically and physically interact with the cement matrix, which leads to the formation of a coherent structure. The interactions involve the formation of polymer films that coat the hydration products, seal the pores, and reduce water permeability. The hydrophobic nature of some polymers contributes to the composite's ability to resist water penetration, thus improving its overall durability [11].

It improves much the microstructure development through combining fly ash with polymers. The improved pore structure diminishes the connectivity among pores and resists aggressive movements of agents such as sulphates through the porous skeleton. This consequently enhances durability performance over long term and maintains its stability in case of environmental attack [12].

III. SULPHATE RESISTANCE IN CEMENT MODIFIED WITH FLY ASH POLYMER COMPOSITES

Sulphate attack is caused when sulphate ions react with the calcium compounds of cement, creating expansion, cracking, and the loss of strength. This chemical degradation type especially occurs in regions with high levels of sulphate, like a marine or industrial environment. Common cement does not possess the needed chemical resistance for long exposure to sulphates. Fly ash promotes sulphate resistance through the pozzolanic reaction, by consuming calcium hydroxide which decreases the level of reactive species available. The produced dense microstructure limits the inward migration of the sulphate ion and slows the chemical reaction or damage progression further. They help prevent sulphate from penetrating by producing a hydrophobic barrier that surrounds the hydration products. Further, the polymer improves the mechanical flexibility of the composite material to take up the applied stress without cracking. Together, fly ash and polymers are providing dual resistance mechanisms to the sulphate attack, incorporating both chemical and physical mechanisms for defense.

IV. SYNTHESIS AND CHARACTERIZATION OF FLY ASH POLYMER COMPOSITES

The preparation of composites with fly ash and polymers is a careful process designed to achieve uniform dispersion and optimal performance. Fly ash, polymer additives, and cement are mixed in precise proportions using a variety of techniques, including dry mixing, slurry preparation, and thermal curing [13]. The fly ash particles are distributed uniformly within the composite, which limits agglomeration, through dry mixing. On the other hand, slurry preparation helps wet the particles well, which is helpful in the bonding between the components. The thermal curing speeds up the setting and hardening processes, enhancing the mechanical properties of the composite [14]. Each of these methods influences the microstructural properties of the material. The final properties of the composite are determined by the choice of polymer type and dosage. For example, thermosetting polymers, epoxy, would result in the enhancement of rigidity and resistance to chemical reactions, whereas the polyethylene would add flexibility and impact resistance in case of thermoplastics. Elastomers like styrene-butadiene rubber (SBR) add toughness and durability [15]. Dosage of polymer additives affects a proper balance between workability and strength. Poor adhesion and performance due to low dosages and deterioration in the structural strength of the material for high dosages. Thus, appropriate dosing and mixing of fly ash and polymer composites is necessary in order to tailor these materials towards the specific needs of applications [16].

Analytical techniques play a critical role in determining the microstructural and chemical properties of fly ash polymer composites. Scanning electron microscopy can reveal detailed images of the composite surface morphology to know about the distribution of particles, porosity, and interfacial bonding. SEM will reveal defects in terms of voids or agglomerations that would adversely affect the strength and durability of the material [17]. The technique used for analysis of the composite is X-ray diffraction, which is able to study the crystalline phases. It offers some insights into hydration products and fly ash-cementitious components interaction. It helps identify unreacted fly ash or other constituents that might influence the performance of the composite. Another critical technique is thermogravimetric analysis, where thermal stability and decomposition behaviour are studied in detail. TGA shows weight changes along with the evolution of temperature so that it relates to the degree of thermal decomposition polymer additives and how stable hydration products would be [18]. Those analytical techniques give a holistic explanation of the composite's microstructure, hydration mechanisms, and interactions at the molecular level. Together they allow scientists and engineers to work on the exact formulation of these composites towards specific environmental as well as mechanical demands [19].

The evaluation of fly ash polymer composites is based on key performance metrics that determine the capability of such a composite to face environmental challenges and sustain stability in the long term. Porosity is an important parameter as it directly affects the resistance of the composite towards water ingress and the entry of aggressive chemical agents [20]. Lower porosity ensures greater durability by minimizing the pathways for moisture and aggressive ions, which might cause chemical degradation. Water absorption is another important parameter, which is a measure of the permeability of the material and its resistance to freeze-thaw cycles, which are a common problem in harsh climates. Sulphate resistance is critical for composites that are exposed to aggressive environments, such as marine or industrial environments [21]. This property is tested by immersing the material in sulphate-rich solutions and checking for its ability to maintain strength and integrity over time. Compressive strength is a primary performance indicator that describes the composite's ability to resist loads without failing. A high compressive strength indicates a strong microstructure and bonding within the composite. Collectively, these metrics allow for a comprehensive description of the composite's durability and suitability for application in specific scenarios. These metrics also lead to improvements in formulation and processing that result in robust and durable materials [22].

V. COMPARATIVE ANALYSIS WITH TRADITIONAL CEMENTITIOUS SYSTEMS

Conventional cement shows limited resistance against sulphate attack as the pore size and amount of calcium hydroxide content is too high, thereby promoting rapid deterioration under aggressive environmental conditions, so a material which should be superior. Fly ash polymer composites overcome these disadvantages by providing greater strength, lesser porosity, and higher chemical resistance. These composites possess synergistic properties that are more effective than traditional cement in performance and sustainability. The fly ash and polymers enhance the performance and reduce the environmental footprint of cement production. Industrial by-products are utilized to minimize energy-intensive processes, and the composites become a cost-effective and environmentally friendly option.

Composite cement is becoming increasingly popular due to its environmental and economic benefits, but it poses difficulties in measuring hydration products because of heterogeneous components and amorphous phases. Advanced image analysis methods, such as Backscattered Electron (BSE) and Energy Dispersive X-ray Spectroscopy (EDS), have been proposed for improved accuracy. These techniques, specifically the combined BSE-EDS method, were used to obtain reproducible measurements of hydration products in composite cement systems with reported proportions of 73.5%, 74.7%, and 68.1% [23]. HSC admixed with silica fume and nanosilica has also been studied with optimal mechanical performance observed at 12% replacement of silica fume and 2% replacement of nanosilica. However, environmental assessments show an increased damage in categories such as acidification and eutrophication, indicating a compromise between performance and environmental impact [24]. Polymer composites have been studied for their durability by comparing the performance of conventional and no-prep/minimally invasive veneers. No-prep veneers showed a survival rate of 100% after nine years, while conventional veneers showed only 9.67%, thus proving to be reliable in dental applications for a long time [25]. LC2 has also been found to be a sustainable alternative SCM, which has better early-age cementing efficiency and lower carbon emissions, but still faces problems in workability and setting time [26]. Hemp fiber-reinforced alkali-activated mortars with fly ash (FA) and granulated blast furnace slag (GBFS) showed improved compressive and flexural strength under carbonation conditions, which indicates the possibility of pore refinement and better performance in cementitious matrices [27].

Fly ash continues to hold promise for improving concrete performance and sustainability. In concrete-face slab applications, dosages of 10–50% improved long-term impermeability but required extended curing for optimal performance. Alkali-activated FA derivatives have also been optimized to achieve compressive strengths of 16.8–22.6 MPa, while simultaneously reducing environmental impact through sustainable concrete formulations [28],[29]. The polymer composites reinforced with FA showed improvements in mechanical properties such as in Acrylonitrile Butadiene Styrene (ABS) matrices and in lignite fly ash (LFA) within polymer matrix composites (PMCs). Addition of FA showed significant enhancement of tensile strength in ABS composites. Enhanced PMCs by LFA containing 5% LFA were reported to be optimum tensile and flexural strength, which contained very minimum voids [30], [31]. Incorporation of natural fibers such as Sida acuta fiber into epoxy composites with FA fillers has also been investigated to achieve superior mechanical and thermal properties. The best tensile and flexural strength were achieved with 2% FA in SAF composites. The interfacial bonding is confirmed through microscopy. These innovations demonstrate the scope for hybrid materials to enhance the lifecycle performance of cementitious systems and support sustainability and environmental conservation [32].

Table 1: Comparative Table of Materials and Properties

Ref. No.	Material Composition	Strength of the Material	Results
23	Composite cement with BSE, EDS techniques	Hydration product proportion 68.1% (BSE-EDS)	Reliable hydration product measurement techniques
24	Silica fume and nanosilica in HSC	Improved compressive strength with 12% silica fume	12% silica fume showed best performance but higher GWP
25	Conventional and no-prep veneers	9.67% (conventional) vs 100% (no-prep) survival rate	No-prep veneers demonstrated higher success rates
26	LC2, FA, GGBS in blended cement	High cementing efficiency, reduced shrinkage	LC2 reduces energy consumption and emissions

27	FA and GBFS with hemp fibers	Compressive strength increase 40%, flexural 34%	Reduced embrittlement and optimal fiber/matrix interface
28	Face slab concrete with 10-50% FA	Optimal impermeability with 30% FA	Improved long-term impermeability with FA
29	Alkali-activated FA concrete	Compressive strength 16.8â€“22.6 MPa	FA qualifies as a sustainable building material
30	FA-reinforced ABS polymer composites	Tensile strength +36.13% with 10wt% FA	Enhanced dimensional stability and surface roughness
31	EP with BF and LFA composites	Tensile strength 53.28 MPa at 5wt% LFA	Minimal voids and high mechanical strength at 5wt%
32	SAFs with epoxy and FA filler	Tensile strength 627 MPa, best at 2wt% FA	Superior mechanical properties with 2wt% FA

VI. FUTURE PROSPECTS AND RESEARCH DIRECTIONS

Optimization of fly ash polymer composite formulations to higher performance metrics in future studies. Aspects in polymer chemistry, etc., as well as additive technologies shall open the avenues for tailored design. Scalability is one promising aspect in fly ash polymer composites for commercial applications in construction. It is further propelled through development of standardised protocols, tested with efficacy and practicability on actual construction projects. These have several advantages; however, some challenges such as cost, availability of materials, and lack of industry standards need to be addressed. There is a need for concerted efforts among researchers, policymakers, and industry stakeholders to overcome the barriers and ensure sustainability.

VII. CONCLUSION

The application of fly ash polymer composites proved to be revolutionary in enhancing durability and sustainability in construction materials. With the addition of fly ash, porosity reduces, chemical resistance is improved, and a dense microstructure is established, which plays a crucial role in long-term stability in aggressive environments. With polymers added, these properties are further improved through adhesion, flexibility, and water resistance. Together, these materials provide a twofold approach to overcoming concerns such as sulfate attack and brittleness in traditional cementitious systems. The systematic employment of analytical tools ensures accurate preparation and better insights into the behaviour of these composites at a microstructural level. Despite the obvious benefits, cost, material availability, and standardization are some of the challenges that need to be overcome for large-scale implementation. Optimizing polymer formulations and developing efficient mix designs will open up tailored applications in different industries. Fly ash polymer composites have great potential for reducing environmental impacts and promoting sustainable development by repurposing industrial byproducts and minimizing the reliance on virgin materials in construction practices. These developments establish fly ash polymer composites as an essential material for modern infrastructure and future innovation.

Conflict of Interest: The corresponding author, on behalf of second author, confirms that there are no conflicts of interest to disclose

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