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A Review of Recent Developments and Advances in Green Concrete

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ABSTRACT

In the past decade, the concrete industry has made significant strides in sustainability and green initiatives. The production of ordinary Portland cement (OPC), a major concrete binder, accounts for about 8% of global CO_2 emissions and depletes natural raw materials. Given the anticipated demand for billions of tons of concrete for future infrastructure, exploring alternative materials is critical. Recent developments highlight the sustainable benefits of alkali-activated binders, supplementary cementitious materials, and recycled materials as replacements for OPC and aggregates. These alternatives not only enhance the properties of concrete but also offer better economic performance compared to conventional materials. Green concrete, produced from eco-friendly waste materials, reduces CO_2 emissions, minimizes environmental harm, and cuts water usage by up to 20%. The green concrete market is driven by reduced carbon footprints, increased construction in developing nations, and lower water consumption. Additionally, green concrete provides excellent thermal insulation and high fire resistance, improving the durability of structures. Utilizing waste materials and admixtures for partial ingredient replacement in green concrete results in improved compressive and tensile strength, better sulfate resistance, decreased permeability, and enhanced workability. These advancements demonstrate the feasibility and benefits of a more sustainable and efficient concrete industry through innovative material use.

***Keywords* —** Green Concrete, OPC, Eco-Friendly, Concrete.

I. INTRODUCTION

Green concrete, a revolutionary advancement in the construction industry, represents a significant shift towards sustainability and environmental stewardship. Traditional concrete production, particularly the use of ordinary Portland cement (OPC), has long been associated with high carbon dioxide (CO_2) emissions, contributing approximately 8% to the world's human-induced CO_2 emissions. Additionally, the production process heavily depletes natural resources, raising concerns about its long-term environmental impact.

As global infrastructure demands continue to rise, the need for sustainable construction materials becomes increasingly urgent. Green concrete, made from eco-friendly waste materials and innovative alternatives to conventional binders and aggregates, offers a promising solution. By incorporating materials such as alkali-activated binders, supplementary cementitious materials, and recycled components, green concrete not only reduces CO2 emissions but also enhances the overall performance and durability of concrete structures.

The adoption of green concrete is driven by several compelling factors. It significantly lowers the carbon footprint of construction projects, aligning with global efforts to mitigate climate change. Additionally, green concrete reduces water usage by up to 20%, which is particularly crucial in regions facing water scarcity. Its production process also generates less waste, further minimizing environmental harm.

Beyond its environmental benefits, green concrete offers practical advantages for construction. It provides excellent thermal insulation and high fire resistance, contributing to the safety and energy efficiency of buildings. Furthermore, structures built with green concrete often exhibit improved compressive and tensile strength, better sulfate resistance, and enhanced workability compared to those made with traditional concrete.

As the construction industry continues to evolve, the integration of green concrete stands as a testament to the potential for innovative materials to drive sustainability without compromising performance. This introduction to green concrete underscores its importance in meeting contemporary construction challenges and paving the way for a more sustainable future.

II. RECENT DEVELOPMENTS IN GREEN CONCRETE

Recent developments in green concrete have transformed the construction industry, addressing environmental concerns while enhancing the material's performance and durability. The traditional production of ordinary Portland cement (OPC), a major component of conventional concrete, contributes significantly to global CO2 emissions and depletes natural resources. To mitigate these issues, researchers and industry professionals have focused on developing sustainable alternatives, resulting in significant advancements in green concrete.

A. *Key Developments*

- **Alkali-Activated Binders**

Alkali-activated binders (AABs) use industrial by-products such as fly ash and slag, activated with alkaline solutions.

These binders significantly reduce CO2 emissions compared to OPC and often enhance the mechanical properties and durability of concrete. They also utilize waste materials, promoting circular economy principles.

- **Supplementary Cementitious Materials (SCMs)**

SCMs, including fly ash, silica fume, and blast furnace slag, are used as partial replacements for OPC in concrete mixes.

Incorporating SCMs improves concrete's strength and durability while reducing the amount of cement required, thus lowering CO2 emissions. They also enhance resistance to various chemical attacks and reduce permeability.

- **Recycled Aggregates**

Recycled concrete aggregates (RCA) and other waste materials like crushed glass and rubber are used to replace natural aggregates in concrete.

Using recycled aggregates reduces the demand for virgin materials, minimizes waste sent to landfills, and decreases the environmental footprint of concrete production. These materials can maintain or even enhance the structural performance of concrete when properly processed and utilized.

- **Bio-Based Additives**

Additives derived from biological sources, such as bacteria and plant extracts, are being explored to improve concrete properties.

These bio-based additives can enhance the self-healing properties of concrete, increase strength, and improve resistance to environmental degradation. They also offer a renewable alternative to synthetic chemicals.

- **Carbon Capture and Utilization (CCU)**

Technologies that capture CO_2 during cement production and incorporate it into concrete mixes are gaining traction.

CCU technologies can significantly reduce the net CO_2 emissions of concrete production. The captured CO_2 can react with concrete components to enhance material properties, such as strength and durability.

Market Drivers

Environmental Regulations: Stricter regulations on CO_2 emissions and waste management are driving the adoption of green concrete technologies.

Economic Incentives: Green concrete can reduce costs associated with raw materials and waste disposal. It also opens up opportunities for government incentives and certifications for sustainable building practices.

Technological Advancements: Innovations in material science and processing technologies have made green concrete more feasible and competitive with traditional concrete in terms of performance and cost.

Practical Benefits

Improved Structural Performance: Green concrete often exhibits enhanced compressive and tensile strength, better sulfate resistance, and decreased permeability compared to traditional concrete.

Thermal Insulation and Fire Resistance: The use of eco-friendly materials can improve the thermal insulation and fire resistance properties of concrete, contributing to safer and more energy-efficient buildings.

Water Conservation: Green concrete production typically requires less water, making it a viable option in regions with water scarcity.

Conclusion

The recent developments in green concrete underscore the potential for sustainable practices to revolutionize the construction industry. By incorporating alternative binders, recycled materials, and innovative additives, green concrete not only addresses environmental concerns but also enhances material properties and performance. As the demand for sustainable construction solutions grows, green concrete is poised to play a crucial role in building a more sustainable and resilient infrastructure for the future.

III. ADVANTAGE OF GREEN CONCRETE

Recent Green concrete, an innovative alternative to traditional concrete, offers numerous advantages that cater to the growing demand for sustainable construction practices. Here are some key benefits:

A. Environmental Benefits

Reduced CO_2 Emissions

Green concrete significantly lowers carbon dioxide emissions compared to traditional concrete. The use of alternative binders such as fly ash, slag, and alkali-activated materials reduces reliance on ordinary Portland cement (OPC), which is a major contributor to global CO2 emissions.

Resource Conservation

By incorporating industrial by-products and recycled materials, green concrete conserves natural resources. It reduces the demand for virgin raw materials like limestone, clay, and natural aggregates, thereby preserving these resources for future generations.

Waste Reduction

The use of recycled aggregates, supplementary cementitious materials (SCMs), and other waste products in green concrete helps divert substantial amounts of waste from landfills. This promotes a circular economy where waste is repurposed into valuable construction materials.

Lower Environmental Impact

Green concrete production often requires less energy and water, further decreasing its environmental footprint. Additionally, the use of bio-based additives and low-impact materials contributes to more sustainable construction practices.

B. Economic Benefits

Cost Savings

Green concrete can lead to significant cost savings through reduced raw material costs and lower waste disposal expenses.

The use of industrial by-products and recycled materials is typically less expensive than procuring new, virgin materials.

Incentives and Certifications

Utilizing green concrete can qualify construction projects for government incentives, tax benefits, and sustainability certifications such as LEED (Leadership in Energy and Environmental Design). These incentives can provide financial advantages and enhance the marketability of green buildings.

Enhanced Durability and Longevity

Green concrete often exhibits improved durability and resistance to environmental degradation, such as better sulfate resistance, decreased permeability, and enhanced resistance to freeze-thaw cycles. This can lead to longer-lasting structures with reduced maintenance and repair costs.

C. Performance Benefits

Improved Structural Properties

Green concrete can offer superior compressive and tensile strength compared to traditional concrete. The inclusion of SCMs and advanced additives can enhance the mechanical properties and overall performance of the concrete.

Thermal Insulation and Fire Resistance

Green concrete provides excellent thermal insulation, which can lead to energy savings in buildings by reducing the need for heating and cooling. Additionally, its high fire resistance enhances the safety and resilience of structures.

Water Conservation

The production of green concrete typically requires less water, which is particularly beneficial in regions facing water scarcity. This conservation effort supports sustainable water management practices in construction.

D. Social Benefits

Health and Safety

The use of non-toxic, eco-friendly materials in green concrete can improve indoor air quality and reduce health risks for occupants and construction workers.

Sustainable Urban Development

By promoting the use of green concrete, urban areas can develop more sustainably, leading to greener cities with lower environmental impacts and enhanced quality of life for residents.

Green concrete presents a compelling solution for the construction industry's sustainability challenges. Its environmental, economic, performance, and social benefits make it a viable and attractive alternative to traditional concrete. By adopting green concrete, the construction industry can significantly reduce its environmental footprint, enhance the durability and efficiency of structures, and contribute to a more sustainable and resilient built environment.

IV. LITERATURE REVIEW

In the context of rapid population growth and increased demand for concrete, Pereza et al. (2024) [1] highlight the significant environmental impacts associated with heightened cement production. Cement production generates approximately 0.87 kg of CO2 per kilogram, and the use of aggregates presents challenges due to rising costs and limited availability. Additionally, the accumulation of recycled concrete aggregate (RCA) and rice husk ash (RHA) exacerbates pollution concerns. This study aims to examine recent research on the utilization of RCA and RHA and their effects on various concrete properties, through a comprehensive evaluation of 80 indexed articles published between 2017 and 2021. Key findings include that the addition of 8% RHA can enhance concrete's compressive strength up to 70 MPa. Moreover, incorporating a combination of 50% RCA and 1.50% basalt microfibers can increase flexural strength by up to 29.44%. Further, the inclusion of 15% RHA results in a compressive strength of 48.8 MPa, while using 10% seashells for fine aggregate and 20% RHA for cement can achieve a flexural strength of up to 65 MPa. Optimal proportions for enhancing concrete properties are identified as a maximum of 8% for RCA and 15% for RHA.

Endale et al. (2023) [2] provide an extensive literature review on rice husk ash (RHA), focusing on its particle properties and their effects on the fresh, mechanical, and durability characteristics of concrete when used as a partial cement replacement. The pozzolanic properties of RHA, influenced by its amorphous silica content, specific surface area, and particle fineness, can be enhanced through controlled combustion and grinding processes for concrete applications. Typically, RHA particles have irregular shapes, porous surface structures, and non-uniform dispersion. RHA-blended cement concrete, due to its finer particle size compared to cement, exhibits improved fresh properties such as workability, consistency, and setting time. The amorphous silica in RHA contributes to better mechanical properties—such as compressive, tensile, and flexural strength—up to an optimal level of RHA content. Furthermore, RHA enhances the durability properties of concrete, improving water absorption, chloride resistance, corrosion resistance, and sulfate resistance. RHA can replace cement by up to 10% to 20% without compromising the performance of concrete, thanks to its high pozzolanic properties. The use of RHA as a partial cement replacement not only conserves resources and manages agricultural waste but also supports a circular economy in the construction industry.

Nehdi et al. (2023) [3] examine a novel technique for the controlled combustion of Egyptian rice husk to address the environmental challenges of its uncontrolled burning and to provide a supplementary cementing material for the local construction industry. The reactor used in this process ensures efficient combustion of rice husk in a short residency time by suspending processed particles with high-velocity jets of process air forced through stationary angled blades. The resulting rice husk ash (RHA) was subjected to analyses for oxide content, X-ray diffraction, carbon content, grindability, water demand, pozzolanic activity index, surface area, and particle size distribution. Concrete mixtures containing various proportions of silica fume (SF) and Egyptian RHA (EG-RHA) produced at different combustion temperatures were prepared and compared. Evaluations were conducted on the workability, superplasticizer and air-entraining admixture requirements, and compressive strength at various ages, as well as resistance to rapid chloride penetration and deicing salt surface scaling. Test results indicate that, unlike RHA produced with existing technologies, the superplasticizer and air-entraining agent requirements did not significantly increase with the new RHA. Concrete mixtures incorporating the new RHA achieved higher compressive strengths than those with similar proportions of SF. Furthermore, RHA concrete demonstrated better resistance to surface scaling compared to SF concrete. While RHA significantly reduced chloride penetration, it remained slightly higher than that achieved by SF concrete.

Ferrara et al. (2023) [7] highlight the negative impacts of CO2 emissions and pollution from agricultural and industrial waste materials on ecosystems. These wastes, often discarded in landfills, contain aluminosilicates, which are essential for creating geopolymer composite (GPC). Unlike ordinary Portland cement (OPC), which is energy-intensive and polluting in terms of CO2 emissions, water usage, and land depletion, GPC offers a more sustainable solution for the construction industry. This research used bibliometric data from the Dimensions database and conducted a scientometric analysis with VOSviewer software (version 1.6.19). The study aimed to explore the development of GPC for construction applications within the context of a circular economy and as a green building material. By analyzing bibliometric records with specific query metrics and keywords (geopolymer, circular economy, and green building materials), the study identified the most influential articles, authors, and journals. This investigation provides significant insights for scholars and policymakers, enhancing their understanding of this expanding research area. From a societal perspective, the study promotes the advancement of geopolymer technology through policies that support the circular economy, such as the implementation of green subsidies for research and development (R&D) and production.

Abate et al. (2023) [8] discuss the increased demand for pulp and paper due to rapid population growth, industrialization, and urbanization. Traditionally, paper manufacturing relies heavily on wood fibers, but the depletion of wood resources and increased deforestation pose significant challenges. To mitigate these issues, non-wood alternatives like corn stalks, sugarcane bagasse, wheat and rice straw, and cotton stalks are being explored to alleviate raw material shortages in pulp and paper production. These non-woody materials can be effectively pulped using methods such as soda/soda-AQ (anthraquinone), organosolv, and bio-pulping. Furthermore, agricultural residues have potential in developing polymeric membranes for separating molecules of different weights across various industries, from water purification to medicinal applications. Despite the current practice of burning agricultural residues in fields, which causes air pollution and health risks, utilizing these residues in paper manufacturing could provide improved financial outcomes for farmers. This article reviews contemporary trends in pulp and paper production from agricultural residues, focusing on different pulping techniques and the application of membranes derived from lignocellulosic materials.

Chavhan et al. (2022) [9] examine the use of waste materials as alternative cement substitutes due to the harmful emissions impacting the atmosphere and the increasing cost of Ordinary Portland Cement (OPC). This study investigates the use of Bamboo Leaf Ash (BLA) as a partial replacement for cement. With water-cement ratios of 0.4 and 0.5, BLA replaced OPC in percentages of 0%, 5%, 10%, and 15% by weight. Concrete cubes (150 x 150 x 150 mm) were tested for compressive strength at 7, 14, and 28 days. The materials used in this investigation included local 'Ultratech' brand Portland cement, bamboo leaves, broken stones, and river sand.

V. CONCLUSIONS

The concrete industry has made significant strides toward sustainability and green initiatives over the past decade. As the production of ordinary Portland cement (OPC) continues to account for a substantial share of global CO2 emissions and the depletion of natural resources, the need for alternative materials has become increasingly critical. Recent advancements have highlighted the potential of alkali-activated binders, supplementary cementitious materials (SCMs), and recycled materials as sustainable replacements for OPC and traditional aggregates. These alternatives not only enhance the performance of concrete but also offer better economic and environmental benefits.

Green concrete, produced from eco-friendly waste materials, has emerged as a promising solution that reduces CO_2 emissions, minimizes environmental harm, and decreases water usage. The market for green concrete is driven by factors such as reduced carbon footprints, increased construction in developing nations, and water conservation. Additionally, green concrete offers practical advantages, including improved thermal insulation, high fire resistance, and enhanced durability, making it a viable option for sustainable construction.

Studies have shown that incorporating waste materials like recycled concrete aggregate (RCA) and rice husk ash (RHA) can significantly improve the mechanical properties of concrete while promoting a circular economy. The adoption of green concrete is supported by stringent environmental regulations, economic incentives, and technological advancements that make it competitive with traditional concrete.

In conclusion, the transition to green concrete represents a significant opportunity for the construction industry to address its environmental impact while maintaining high performance and durability standards. By leveraging innovative materials and sustainable practices, the industry can contribute to a more sustainable and resilient built environment. The ongoing research and development in this field underscore the potential for green concrete to revolutionize construction practices and support global sustainability goals.

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