RESEARCH ARTICLE OPEN ACCESS

A Comprehensive Review on the Utilization of Sisal Fiber and Eggshell Waste in Sustainable Self-Compacting Concrete

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ABSTRACT

Sustainable construction materials are gaining increasing attention in the civil engineering sector due to growing environmental concerns and the depletion of natural resources. This review paper focuses on the potential use of sisal fiber and eggshell waste as eco-friendly additives in self-compacting concrete (SCC). Sisal fiber, derived from the agave sisalana plant, offers high tensile strength and biodegradability, while powdered eggshells, rich in calcium carbonate, present a valuable way to recycle agricultural waste. The review critically summarizes previous studies on the physical, mechanical, and durability properties of SCC when partially replaced with sisal fiber and eggshell powder. The paper also highlights gaps in the literature and suggests directions for future research.

Keywords —Construction, Concrete, Self-Compacting Concrete (SCC), Sisal Fiber, Eggshell Waste.

I. INTRODUCTION

Concrete remains the most extensively utilized construction material worldwide due to its versatility, durability, and ease of production. It plays a crucial role in infrastructure development, urbanization, and economic growth. However, the production of concrete, especially the manufacturing of Portland cement, is associated with significant environmental impacts. Cement production alone is responsible for nearly 7–8% of global carbon dioxide (CO_2) emissions. This has raised concerns among engineers, researchers, and policymakers about the sustainability of concrete and the urgent need to develop more eco-friendly alternatives.

To address this environmental challenge, researchers are focusing on sustainable construction practices that involve partial replacement of conventional concrete materials with renewable, recycled, or waste-based resources. Among the various alternatives, the use of natural fibers and industrial/agricultural waste by-products is gaining attention. Two such promising materials are sisal fiber and eggshell waste.

Sisal fiber, extracted from the leaves of the Agave sisalana plant, is a biodegradable and renewable material widely available in tropical and subtropical regions. It possesses high tensile strength, low density, and good flexibility, making it a suitable reinforcement material in concrete composites. The inclusion of sisal fiber in concrete can significantly improve mechanical properties such as tensile strength, flexural strength, and impact resistance. Additionally, it enhances the ductility and toughness of concrete, reducing crack propagation and improving structural durability.

On the other hand, eggshell waste, a by-product generated in large quantities by the food industry and households, is typically disposed of in landfills, posing environmental disposal issues. However, eggshells are primarily composed of calcium carbonate ($CaCO_3$), which makes them chemically similar to limestone, the primary raw material used in cement manufacturing. After suitable treatment and grinding, powdered eggshell can act as a partial replacement for cement in concrete mixes. Its fine particles help fill micro-voids in the concrete matrix, enhancing workability, reducing permeability, and improving early-age strength to some extent.

The concept of combining sisal fiber and eggshell powder in concrete aligns with circular economy principles, promoting the reuse of waste materials while reducing dependence on natural resources.

Integrating these materials into Self-Compacting Concrete (SCC) offers additional benefits. SCC is a special type of high-performance concrete that flows under its own weight, fills formwork effortlessly, and passes through congested reinforcement without the need for mechanical vibration. Maintaining the required workability and flowability in SCC while incorporating fibrous and powdery waste materials poses a unique engineering challenge but also presents an opportunity to produce more sustainable and eco-friendly concrete.

This review paper focuses on the combined utilization of sisal fiber and eggshell waste in SCC. It aims to explore their individual and combined effects on the fresh and hardened properties of concrete, including workability, strength characteristics, and durability. The paper also highlights findings from past studies, identifies existing research gaps, and suggests potential areas for further investigation to optimize the use of these sustainable materials in modern concrete technology.

II. OVERVIEW OF SELF-COMPACTING CONCRETE (SCC)

Self-Compacting Concrete (SCC) is a high-performance concrete that was developed to overcome the challenges of placing and compacting concrete in heavily congested reinforcement zones, where conventional vibration techniques are either impractical or ineffective. Unlike traditional concrete, SCC has the ability to flow and fill intricate formworks under its own weight without the need for external compaction or vibration. The successful performance of SCC relies heavily on its carefully designed mix proportions, including the use of superplasticizers and viscosity-modifying agents to balance flowability and segregation resistance. The primary characteristics that define SCC include high flowability, enabling it to spread easily; passing ability, allowing it to flow through tight spaces around reinforcements; segregation resistance, ensuring uniformity without coarse aggregate separation; and sufficient mechanical strength to meet structural requirements. With growing emphasis on sustainability, SCC has become an attractive option for incorporating industrial by-products and natural fibers to enhance performance while reducing environmental impact..

III. SISAL FIBER IN CONCRETE

3.1 Properties of Sisal Fiber

Sisal fiber, obtained from the leaves of the Agave sisalana plant, is a natural, biodegradable, and renewable resource widely available in tropical and subtropical regions. Known for its high tensile strength ranging between 400 to 700 MPa and low density (approximately 1.2 to 1.5 g/cm^3), sisal fiber offers an eco-friendly and cost-effective reinforcement option for concrete composites. Its surface texture and length-to-diameter (aspect) ratio contribute to effective bonding within the cementitious matrix, making it an ideal candidate for improving concrete's mechanical performance.

3.2 Effects on Fresh Concrete

While sisal fiber enhances mechanical properties, its incorporation in fresh concrete presents challenges, especially concerning workability. The presence of fibers increases inter-particle friction, often leading to reduced flowability and slump. In SCC, maintaining self-flow characteristics becomes difficult at higher fiber contents due to fiber balling, segregation, and blockage during placement. Research indicates that keeping the fiber dosage below 2% by weight of cement helps in maintaining the desired flow properties of SCC without significant loss in workability.

3.3 Effects on Hardened Concrete

In hardened SCC, sisal fiber shows significant benefits in improving tensile and flexural strength by bridging micro-cracks and restricting their propagation. It enhances impact resistance, ductility, and energy absorption capacity, making the concrete tougher and more durable under dynamic or sudden loading conditions. However, an excessive quantity of fiber may adversely affect compressive strength, reduce surface finish quality, and increase porosity due to improper compaction. Optimal dosages ensure a balance between enhanced tensile properties and acceptable compressive strength.

IV. EGGSHELL WASTE AS CEMENT REPLACEMENT

4.1 Chemical Composition

Eggshell waste, mainly generated from the food processing industry and household kitchens, presents a sustainable option for cement replacement. Composed predominantly of calcium carbonate ($CaCO_3$), its chemical composition is similar to limestone, a primary raw material in cement production. To utilize it effectively, eggshells are washed, dried, ground, and sieved to obtain a fine powder with high pozzolanic reactivity. This fine powder can serve as a partial replacement for cement in concrete mixes, contributing to reduced cement consumption and lower carbon emissions.

4.2 Influence on Concrete Properties

In fresh SCC, the addition of eggshell powder improves workability due to its micro-filler effect. The fine particles fill voids between cement grains and aggregates, enhancing the slump flow and viscosity of the mix. Studies show that replacing up to 15–20% of cement with eggshell powder increases the slump flow, making it suitable for SCC applications. Regarding hardened properties, a moderate addition of eggshell powder (typically up to 15%) can result in improved compressive strength due to pore refinement and enhanced cement hydration. Moreover, it contributes to better durability by reducing permeability and increasing resistance to acid attacks. However, excessive eggshell content beyond the optimum level may lead to strength reductions due to dilution of the cementitious matrix.

V. COMBINED EFFECT OF SISAL FIBER AND EGGSHELL POWDER IN SCC

The simultaneous use of sisal fiber and eggshell powder in SCC has shown promising synergistic effects, as observed in recent studies including Sharma et al. (2024). While sisal fibers alone tend to reduce the workability of concrete, the addition of eggshell powder helps counterbalance this effect by improving flowability and reducing internal friction. The combination allows for the production of SCC with satisfactory workability and enhanced mechanical performance. In terms of compressive strength, mixes containing 1–2% sisal fiber along with up to 15% eggshell powder demonstrated optimum results, offering strength improvements over control mixes without additives. Furthermore, the composite mix exhibited better durability against acid attack, with lower strength losses over time compared to traditional concrete. The presence of fibers enhanced the split tensile strength by bridging internal cracks, while the eggshell powder contributed to matrix densification and durability. Overall, the combined use of sisal fiber and eggshell waste in SCC offers a sustainable solution with improved mechanical and durability performance, supporting the goals of eco-friendly and resource-efficient construction.

VI. CONCLUSIONS

The utilization of sisal fiber and eggshell waste in SCC offers a promising approach toward sustainable concrete production. Their combined use improves mechanical properties, durability, and environmental performance. However, optimal mix proportions must be carefully selected to balance workability and strength. More extensive field trials and standardization efforts are required before large-scale implementation.

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