# Enhancing Concrete Efficiency Through Sustainable Materials for Waste Management

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**Abstract:**
The rising cost of construction materials, particularly cement and reinforcement bars, has significantly increased construction expenses. Additionally, the environmental concerns associated with cement production and the disposal of agricultural waste necessitate sustainable solutions. This study explores the potential of Coconut Fiber Ash (CFA) in combination with micro silica (MS) as an admixture to enhance concrete performance. While coconut fiber has traditionally been used to improve the tensile strength of concrete, this research investigates the impact of CFA on strength and durability. Experimental results indicate that incorporating 5%, 10%, and 15% CFA-MS leads to an increase in compressive and flexural strength at 28 days **by** 17.5%, 22.78%, 11.4% and 57.5%, 62.2%, 50.24%**,** respectively. Furthermore, tensile strength improved by 7.54%, 14.04%, and 24.96% for the same proportions. However, as the CFA-MS content increased, a slight reduction in compressive and flexural strength was observed, while split tensile strength showed significant enhancement. Additionally, flexural behaviour studies on CFA-MS concrete beams demonstrated their structural efficiency. This study highlights the potential of CFA-MS-modified concrete as a sustainable alternative in construction, contributing to improved mechanical performance and eco-friendly material utilization.

**Keywords:** Coconut fiber Ash, Microsilica, Mechanical Performance.

## 1. Introduction:

Concrete remains the most extensively used construction material, renowned for its strength, durability, and enhanced flexural performance. However, the rapid pace of technological advancement has intensified the depletion of natural resources, including deforestation, underscoring the urgent need for sustainable building solutions[1]. However, growing environmental concerns over the high energy consumption and $CO_2$ emissions associated with cement production have increased efforts to reduce its usage by incorporating sustainable alternative materials[2]. Coconut fiber, a natural byproduct of commercial coconut processing, is increasingly recognized for its potential in addressing environmental challenges. The sustainability and eco-friendliness of coconut fiber make it a preferred choice for various applications[3]. Coir is a durable, stiff, and biodegradable lignocellulosic fiber extracted from the fibrous mesocarp of coconut fruits, constituting approximately 25% of the nut. Beyond its cost-effectiveness and renewability, coconut fiber is biodegradable and environmentally beneficial[4]. When used as a raw material or filler in composite products, it offers low bulk density and high thermal conductivity, contributing to developing lightweight materials with superior thermal properties[5]. Among natural fibers, coconut fiber stands out for its remarkable tensile strength of 21.5 MPa[6]. Additionally, it enhances composite durability while providing antibacterial properties, mold resistance, temperature stability, and effective sound absorption, further expanding its potential in sustainable material innovation. Ismail Shah et al. [7] conducted a study on High-Strength Concrete (HSC) incorporating coconut and sisal fiber at varying content levels of 0.5%, 1%, and 1.5% by cement mass. The results indicated that at 1% fiber content, coconut fibers increased the compressive strength of HSC by 33%, while sisal fibers contributed to a 24% improvement. Syed et al.[8] reported that incorporating processed coir fiber into concrete reduced workability while affecting compressive strength (CS), increasing it by 0.6% or decreasing it by 1.2%, depending on the mix composition. Senthilkumar et al. [9] investigated the effect of fibrillation on coconut fibers in epoxy composites and found that fibrillated fibers significantly improved tensile strength and damage resistance. Although coir fiber is utilized in concrete, a significant amount still goes to waste. It can be converted into ash and incorporated into concrete to address this[10]. Previous research explored the potential of coconut shell ash (CSA) waste as a partial replacement for cement. The findings indicated that CSA waste possesses pozzolanic properties, which enhance the mechanical performance of concrete, particularly its compressive strength. Furthermore, as Portland cement continues to absorb water over time, the pozzolanic reaction of CSA contributes to densifying the concrete's microstructure[11]. This process supports a continued increase in the compressive strength of concrete as it matures. Most existing studies on incorporating coconut waste in concrete production examine its role in replacing a single aggregate component, such as cement, gravel, or sand, or explore its application as fiber reinforcement. Although this approach aids in managing and disposing of coconut waste, it falls short of fully harnessing its potential for sustainable applications in the construction industry. In this study, coir fiber ash (CFA) with micro silica is introduced as an additive to enhance the strength properties of concrete while promoting environmental sustainability.

## 2. Research Significance:

Incorporating coconut shell ash (CSA) in concrete serves a dual purpose: it mitigates waste disposal challenges and enhances the material's structural performance, particularly its strength. Converting coconut fibers into ash provides a more efficient and sustainable alternative to conventional disposal methods. Unlike the direct use of coconut waste materials such as shells, coir fibers, and husks, integrating CSA into concrete maximizes its pozzolanic potential, promoting environmental sustainability and innovation in construction materials.

## 3. Materials & Methods:

### 3.1 Materials

The concrete test specimens were prepared using Ordinary Portland Cement (OPC), Coir Fiber Ash (CFA), fine aggregate, and coarse aggregate. Manufactured sand (M-sand), sourced locally with a maximum grain size of 4.75 mm, was used as the fine aggregate, while crushed gravel, with a maximum size of 12.5 mm, served as the coarse aggregate. Coir fibers, obtained as an agricultural byproduct, were sun-dried for two to three days before being incinerated to produce Coir Fiber Ash (CFA). The incineration process resulted in the combustion of organic matter, generating ash, flue gas, and heat. The collected ash was carefully transferred to a sealed metal container to ensure complete cooling before handling. To achieve a fineness comparable to cement, the cooled ash was sieved through a 90-micron sieve, enhancing its suitability for concrete applications. As per ASTM C618, the chemical analysis of CFA revealed that the combined content of silicon dioxide ($SiO_2$), aluminum oxide ($Al_2O_3$), and iron oxide ($Fe_2O_3$) was below

50%, with a loss on ignition of less than 6%. This composition closely aligns with the properties of Class C fly ash pozzolana.

**3.2. Methodology:**

The M30-grade concrete mix was designed per IS 10262:2019, incorporating Coir Fiber Ash and Microsilica (CFAMS) as partial cement replacements at 0%, 5%, 10%, and 15%. Mixes were labeled based on their CFAMS replacement level, with CFAMS10 denoting a 10% substitution. Due to CFAMS's high water absorption, additional water was added to maintain a consistent water-to-binder ratio of 0.45.Concrete specimens were prepared using the conventional mixing method. Aggregates and CFAMS were dry-mixed for four minutes, followed by cement incorporation and an additional five-minute mixing. Specimens were compacted with a table vibrator, de-molded after casting, and cured in a water tank. Three specimens were tested for each mix proportion at 7, 14, and 28 days to assess strength development.

**3.3 Testing:**

Experimental tests were conducted on hardened concrete specimens to evaluate their mechanical properties and flexural behaviour. Table 3 provides a detailed overview of the specimen types, testing ages, and the standards followed for each test. A Universal Testing Machine (UTM) with a 100 kN capacity was used to assess the mechanical performance of the concrete, including compressive strength, split tensile strength, and flexural strength.

**3.4 workability and Mechanical Properties:**

Workability, defined as the ease of placing fresh concrete without segregation, was assessed using the slump cone test as per IS 1199:2018 for CC and GGPA concrete mixes. Mechanical properties were evaluated after 7, 14, and 28 days of curing, following IS 516:1959 for compressive and flexural strength and IS 5816:1999 for split tensile strength. Compressive strength was tested using 100 × 100 × 100 mm cubic specimens, while 100 × 200 mm cylindrical specimens were utilized for split tensile strength, with 3 mm thick, 25 mm wide plywood strips placed between the loading platens. The same Universal Testing Machine (UTM) with a 100 kN capacity was used for both tests. Flexural strength was determined using the three-pin method on 100 × 100 × 500 mm concrete prisms, with an eccentric line load uniformly applied at the beam's center.

## 4. Results and discussion:

### 4.1 Workability Properties:

As shown in Fig. 1, the slump test results indicate a gradual workability reduction with increasing concrete CFA content. The control mix (CFAMS0) exhibited the highest slump value of 130 mm, signifying superior workability due to pure cementitious material. With the inclusion of 5% CFA (CFAMS5), the slump value declined to 110 mm, followed by 100 mm for CFAMS10, and further reduced to 90 mm for CFAMS15. This trend highlights that higher CFA replacement reduces concrete's fluidity, primarily due to its higher surface area and increased water absorption capacity. The reduced slump at higher CFA percentages suggests the necessity of water-reducing admixtures or superplasticizers to maintain workability while incorporating CFA in concrete mixtures.

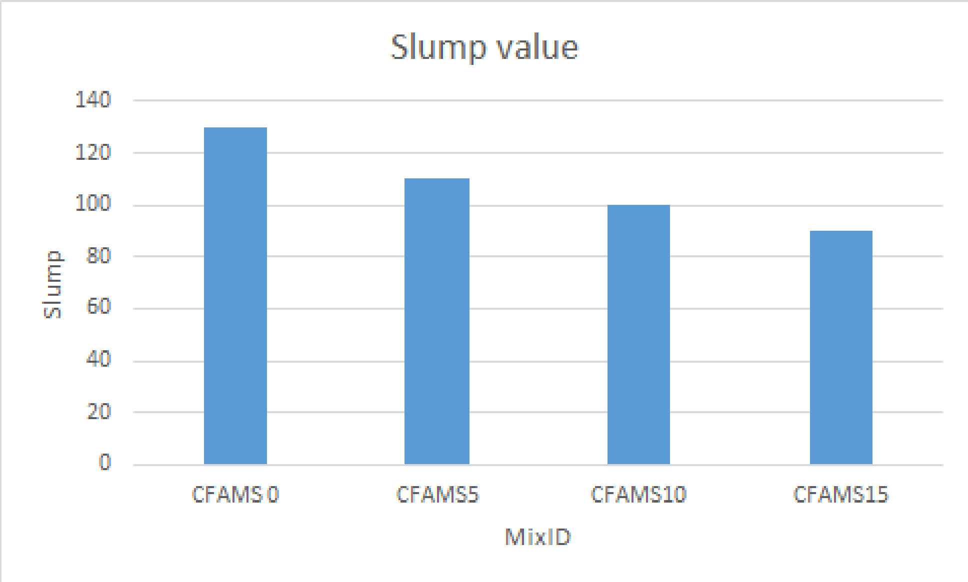


**Fig-1**

### 4.2 Mechanical Properties:

#### 4.2.1 Compressive Strength:

Fig 2 depicts the compressive strength of CFAMS concrete. The CFAMS5 blend exhibited enhanced performance, reaching 18 MPa at 7 days, 24 MPa at 14 days, and 38 MPa at 28 days**.** This upward trajectory continued with CFAMS10, which demonstrated the highest recorded values of 22 MPa at 7 days, 26 MPa at 14 days, and 41 MPa at 28 days. The significant strength gain at this level suggests that the finer particles of CFA effectively fill voids in the concrete matrix, refining its microstructure and enhancing its overall integrity. However, beyond 10% CFA replacement, a decline in compressive strength was observed. The CFAMS15 mix, while still outperforming the control, registered 17 MPa at 7 days, 22 MPa at 14 days, and 36 MPa at 28 days. This reduction can be attributed to the dilution effect, where excessive CFA content compromises the cementitious matrix, diminishing its bonding capacity. The results indicate that CFA, when incorporated up to 10%, significantly enhances compressive strength due to its filler effect and microstructural refinement. Beyond this threshold, the structural integrity diminishes, highlighting the importance of optimizing CFA dosage to maximize performance without compromising durability. A similar trend was observed in the study by Bheel et al. [12], where replacing cement with coconut shell ash and groundnut shell ash up to 10% yielded optimal compressive strength at 28 days. Comparable findings have also been reported by other researchers conducting similar investigations. Other researchers have also conducted similar investigations, reporting comparable results.[13]

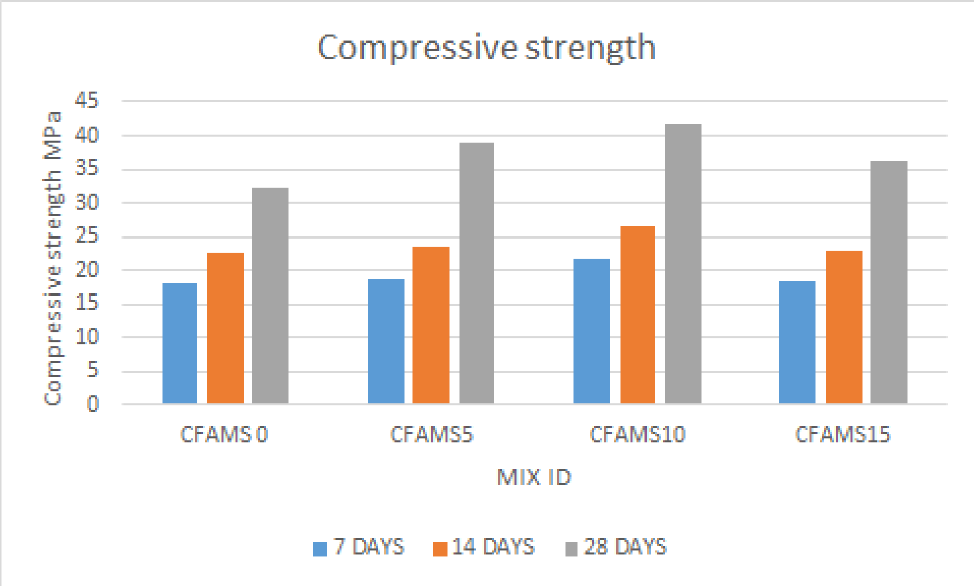


**Fig-2**

### 4.2.2 Split tensile strength:

Concrete's tensile strength is inherently low due to its compressive nature. Figure 3 shows the splitting tensile strength of control (CFAMS 0) and CFA-modified concrete at 7, 14, and 28 days. The control sample achieved 1.5 MPa, 2.2 MPa, and 5.0 MPa, respectively. CFA incorporation enhanced strength, with CFAMS 5 reaching 5.5 MPa, CFAMS 10 at 6.0 MPa, and CFAMS 15 peaking at 6.7 MPa at 28 days. This increase is attributed to CFA's large surface area, which improves particle packing and bond strength. However, excessive CFA may cause a dilution effect, reducing strength gain.

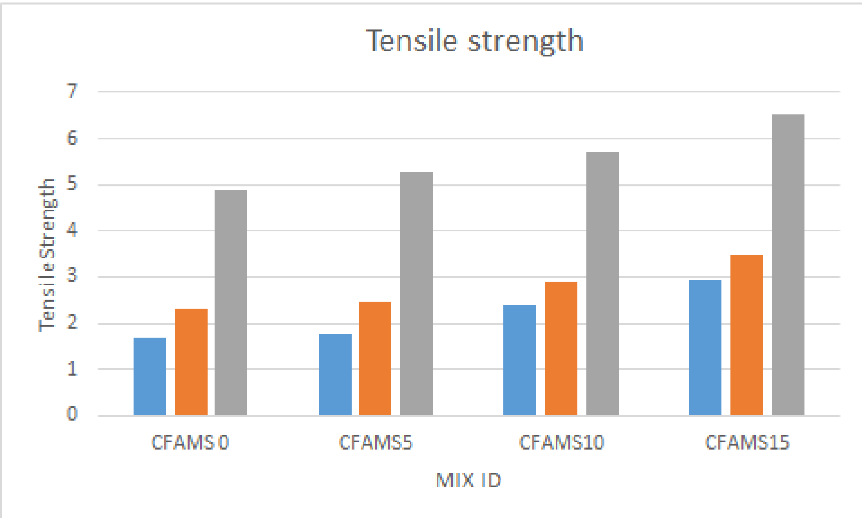


**Fig-3**

### 4.2.3 Flexural Strength :

Figure 4 highlights the progression of flexural strength of control (CFAMS 0) and CFA-modified concrete at 7, 14, and 28 days. The control sample showed modest gains, reaching only 2.2 MPa at 28 days below the ACI-recommended 3.5 MPa. CFAMS incorporation significantly enhanced strength. CFAMS 5 improved to 5.0 MPa, while CFAMS 10 peaked at 5.5 MPa at 28 days. However, CFAMS 15 slightly declined to 4.2 MPa, indicating an optimal CFA threshold. This enhancement is linked to CFA's finer particles, which improve bonding and reduce voids. Beyond 10% CFA, excessive water absorption disrupts mixing, reducing strength.

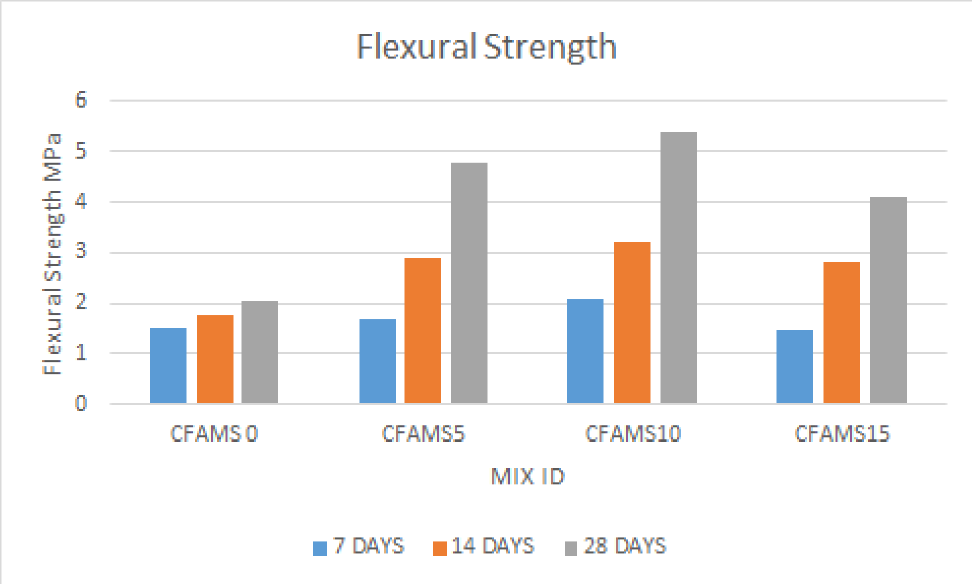


**Fig-4**

**4.2.4 RCC Beams :**

Beam deflection is a critical parameter in assessing structural performance. This study examined the load-deflection response at mid-span (L/2). As anticipated, deflection at L/2 was consistently more significant than at L/3, with a difference of approximately 6 mm, which aligns with pure bending theory. This occurs due to the concentrated load 2P2P2P at L/2, whereas at L/3, the load is distributed, leading to a lower deflection. Numerical analysis further confirms that deflection at L/2 is around 15% higher than at L/3.Experimental results (Fig. 5) reveal that the maximum deflection for normal concrete beams was 16.8 mm at 32 kN for the control sample (0% CFA). As CFAMS content increased, deflection decreased, with 10% CFAMS recording 13.1 mm at the same load. A similar trend was observed at intermediate loads at 22.5 kN; deflection was 15 mm for 0% CFA, reducing to 12 mm for 15% CFA. These findings suggest that incorporating CFAMS enhances beam stiffness, minimizing deflection under load. However, beyond an optimal threshold, excessive CFA may compromise ductility. The load-deflection characteristics indicate that normal concrete beams without CFA experience higher deflections, affirming traditional structural behavior under applied loads.

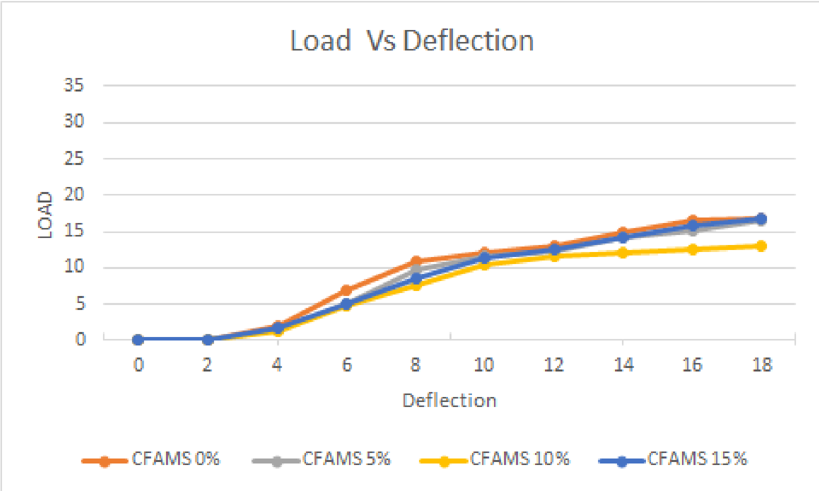


**Fig-5**

**5. Conclusion:**

- Incorporating up to 10% CFA enhances compressive strength, with CFAMS10 reaching 41 MPa at 28 days, but exceeding this limit reduces cementitious efficiency, leading to strength deterioration.
- CFA modification improves splitting tensile strength, with CFAMS15 reaching 6.7 MPa at 28 days, surpassing the control mix due to CFA's fine particles, which refine the concrete matrix and enhance bonding.
- Control concrete (CFAMS0) failed to meet ACI's recommended 3.5 MPa flexural strength at 28 days, while CFAMS10 peaked at 5.5 MPa, demonstrating CFA's effectiveness in reducing voids and enhancing bonding. However, beyond 10% CFA, excessive water absorption disrupted mix quality, leading to a decline in flexural strength.
- CFA incorporation enhanced beam stiffness, reducing deflection under applied loads. At 32 KN, deflection decreased from 16.8 mm (0% CFA) to 13.1 mm (15% CFA), demonstrating improved rigidity. However, excessive CFA compromised ductility, highlighting the need for an optimized balance between strength and flexibility.
- CFA up to 10% is an adequate partial cement replacement, enhancing mechanical properties while maintaining structural integrity. However, exceeding this limit leads to mixed instability and excessive water demand, hindering performance. These findings align with existing research, reinforcing CFA's viability as a sustainable, performance-enhancing material in concrete applications.

**Scope for future work:**

- Supplementary cementitious materials (SCMs) such as silica fume, alccofine, or fly ash can increase the CFA replacement percentage in concrete while maintaining strength and durability. These admixtures enhance pozzolanic activity, particle packing, and overall matrix refinement, counteracting the dilution effect of excessive CFA.
- Conduct life cycle assessments (LCA) to quantify the carbon footprint reduction achieved by using CFA while exploring cost-benefit analyses to establish CFA as a viable, eco-friendly alternative for commercial concrete production.
- Exploring the incorporation of nano-silica, nano-clay, or graphene oxide to enhance strength, durability, and crack resistance while improving early-age strength to reduce curing time in high-performance concrete applications.

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