Article

Development of Sustainable Concrete Tiles Using Bamboo Fibers and Fly Ash

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Abstract

The construction industry is a major contributor to global carbon emissions, primarily due to the high cement content in concrete. This study explores the development of sustainable concrete tiles using bamboo fibers and fly ash as partial replacements for cement and fine aggregates. Bamboo fibers were incorporated to enhance tensile strength, while fly ash was used to reduce cement content and improve compressive properties. Lab experiments were conducted to evaluate the mechanical performance of the composite. Our results indicate that an optimal mix of 2% bamboo fibers and 5% fly ash achieves a balance between strength and sustainability. These findings demonstrate the potential of this eco-friendly material for non-structural applications such as tiles, contributing to reduced carbon emissions and promoting sustainable construction practices. The environmental impact of conventional concrete extends beyond just carbon emissions. The extraction of raw materials like sand, gravel, and limestone leads to habitat destruction and landscape degradation. The energy-intensive processes involved in quarrying, transporting, and manufacturing cement and aggregates further contribute to the industry's environmental footprint. Moreover, the vast quantities of water required for concrete production add to the strain on freshwater resources, especially in water-scarce regions. Addressing these multifaceted environmental challenges necessitates a paradigm shift towards more sustainable material choices and production methods within the construction sector.

Keywords: bamboo fibers; fly ash; sustainable concrete; carbon emissions; non-structural applications; eco-friendly materials; concrete tiles; green construction

1. Introduction

1.1 Background and Context

The construction industry is one of the largest contributors to global carbon emissions, with cement production alone accounting for approximately 8% of the world's CO_2 emissions [1]. Concrete, being the most widely used construction material, consumes vast amounts of natural resources and energy, leading to significant environmental degradation. While structural concrete requires high strength, non-structural applications such as tiles offer an opportunity to incorporate eco-friendly materials with lower strength requirements.

Fly ash, a by-product of coal combustion, has been widely recognized for its pozzolanic properties, which contribute to the long-term strength and durability of concrete [2]. By replacing a portion of cement with fly ash, the carbon footprint of concrete production can be significantly reduced [3]. Similarly, bamboo fibers, known for their high tensile strength and rapid renewability, offer a sustainable solution to improve the tensile properties of concrete [4]. The combination of these materials presents a unique opportunity to create eco-friendly concrete tiles that align with global sustainability goals [5]. Incorporating such alternatives not only promotes waste utilization but also encourages circular economy practices within the construction sector. These developments are gaining attention as industries shift toward greener building techniques. Moreover, using such composites in tile production can help balance environmental responsibility with functional and aesthetic performance.

1.2 Research Gap

While previous studies have explored the use of fly ash and bamboo fibers in structural concrete, limited research has been conducted on their application in non-structural elements such as tiles. Most studies focus on either fly ash or bamboo fibers individually, with little attention given to their combined use in lightweight, sustainable tiles [6], [7]. This research gap highlights the need for a comprehensive study on the development of sustainable concrete tiles using both fly ash and bamboo fibers. Such a study could bridge the gap between material innovation and practical application, especially in areas prioritizing low-cost and eco-conscious construction. A dual incorporation strategy may not only improve mechanical behavior but also enhance the aesthetic versatility of concrete tiles. Additionally, the integration of such materials can open new avenues in the prefabrication industry, where lightweight and durable products are increasingly in demand.

1.3 Research Objectives and Significance

This study's central aim is to create sustainable concrete tiles by incorporating bamboo fibers and fly ash, using them as partial substitutes for traditional cement and fine aggregates. Our specific objectives for this research include:

- Evaluating the mechanical properties of these newly developed bamboo-fly ash concrete tiles. This means thoroughly testing their strength, durability, and other physical characteristics to ensure they meet performance expectations.

Determining the optimal mix proportions of bamboo fibers and fly ash. The goal here is to find the perfect balance that maximizes both the tile's strength and its environmental benefits.

- Assessing the environmental benefits gained by reducing the amount of cement used. This involves quantifying how the inclusion of fly ash and bamboo fibers contributes to a lower carbon footprint in concrete production.

This research contributes to the growing body of knowledge on sustainable construction materials and provides a practical solution for reducing the environmental impact of concrete production. By leveraging industrial by-products like fly ash and renewable resources like bamboo, this study aligns with global efforts to promote sustainable development in the construction industry [7]. It emphasizes the importance of adopting resource-efficient practices without compromising performance or durability. The outcomes of this work may inform future material guidelines and sustainable building codes. In doing so, the research not only advances academic inquiry but also supports real-world implementation of green construction strategies.

2. Research Methodology

2.1 Overview

This study is centered on creating sustainable concrete tiles by incorporating bamboo fibers and fly ash. We carried out laboratory experiments to assess the mechanical characteristics of this new composite material, specifically looking at its compressive strength, workability, and density. The subsequent sections will provide a detailed account of the materials, the mix designs, and the testing methods employed in this research. This meticulous approach guarantees a deep understanding of how these environmentally friendly additives impact the basic properties of the concrete mix. This understanding, in turn, is crucial for determining whether the resulting tiles are suitable for practical, real-world uses. While our primary focus was on mechanical properties, optimizing the mix design based on these initial tests implicitly addressed other important aspects like durability, how much water the tiles absorb, and their overall cost-effectiveness.

2.2 Materials

The materials used in this study included Ordinary Portland Cement (OPC) conforming to ASTM standards, Class F fly ash obtained from a local thermal power plant, as shown in Figure **3.** Cured Tiles, a. Before curing b. After curing

2.7 Testing

Compressive Strength: Tested using a Compression Testing Machine by ASTM C39 standards, as shown in Figure 4.

Workability: Assessed using slump tests to ensure the mix was suitable for casting and handling.

Tile testing: Concrete tiles were also fabricated and subjected to dedicated tests, including flexural strength (ASTM C293), water absorption (ASTM C373), and load resistance, simulating real-world application scenarios for roofing and ceiling panels.

Figure 4. Tested tiles, a. Layers of aggregate b. Cracks appeared after loading

(Part b) treated bamboo fibers (Part a), locally available manufactured sand, crushed stone with a maximum size of 20 mm, and clean potable water for mixing and curing. Choosing these specific materials was incredibly important. The treated bamboo fibers and Class F fly ash are key to getting the sustainable concrete tiles to perform well, both mechanically and environmentally. Plus, by using aggregates and fly ash that were sourced locally, we further boosted the project's sustainability by cutting down on carbon emissions from transportation.

2.3 Mix Design

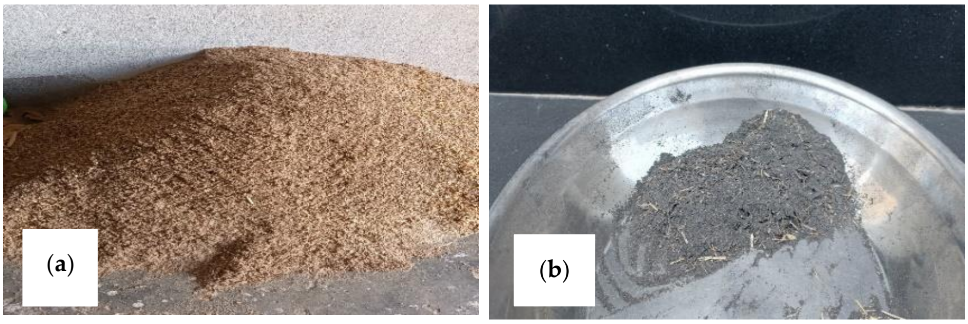

Figure 1. Preparation of bamboo Fibers and their mixture, a. Bamboo Fibers, and b. Bamboo Fibers mixed with fly ash

To begin, we used a standard concrete mix ratio of 1:2:4 (cement: fine aggregate: coarse aggregate). From this base, we created five different concrete compositions. One was a control mix, containing no fly ash or bamboo fibers. The other four mixes incorporated varying amounts of fly ash (5%, 10%, 15%, and 20%) and bamboo fibers (2%, 4%, 6%, and 8%). This methodical approach to changing the proportions of fly ash and bamboo fibers will allow us to thoroughly analyze how each material, both individually and together, affects the concrete's properties. The specific percentages we chose for these additives are practical for actual construction uses, helping us pinpoint the ideal amounts for making concrete tiles that are both stronger and more sustainable.

2.4 Preparation of Bamboo Fibers

Raw bamboo was cleaned, dried, and treated with a borax solution to enhance durability and resistance to biological degradation. The treated bamboo was ground and sieved to achieve the desired particle size [8]. Borax treatment is a critical step because organic materials like bamboo can easily absorb moisture and get attacked by microbes. By making the bamboo last longer and more stable, this treatment ensures the fibers help the concrete tiles in the long run instead of becoming a weak spot. Following this, the grinding and sieving processes were essential for getting a consistent particle size. This consistency directly affects how easily the concrete mix can be worked with and how evenly the fibers spread throughout it, which in turn, directly influences the final strength and performance of the tiles.

2.5 Casting and Curing

A total of 45 cylindrical specimens (150 mm diameter × 300 mm height) as shown in Figure 2 were cast to evaluate the mechanical properties of the bamboo and fly ash concrete mix. Each composition had 9 specimens, tested at curing ages of 7, 14, and 28 days. The fabricated concrete tiles were also demolded after 24 hours and cured in water for up to 28 days, as shown in Figure **3** to ensure proper hydration and strength development.

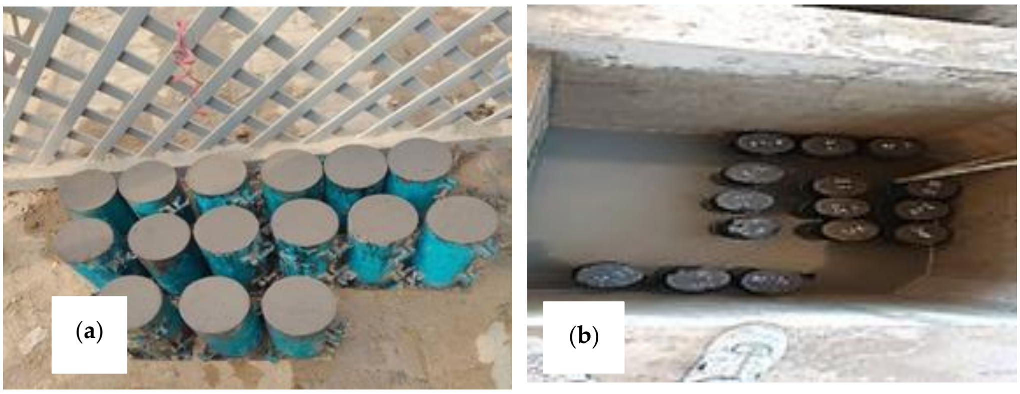

Figure 2. Casting and Curing, a. Specimens Submerged in a curing tank, and b. Specimens were placed for air curing before testing

2.6 Density

The density of the concrete decreased as the percentage of fly ash and bamboo fibers increased. The mix with 2% bamboo fibers and 5% fly ash had a density of 2300 kg/m³, while the mix with 4% bamboo fibers and 10% fly ash had a density of 2200 kg/m³ [9]. This makes sense because both fly ash and bamboo fibers are generally lighter than the cement and aggregates, they replaced.

The fact that these additives make the concrete lighter is a big plus, especially for things like tiles that don't need to hold up heavy loads. It means lower transportation costs and tiles that are easier to handle and install. This also helps reduce the overall weight of buildings, which can lead to more efficient and potentially less costly structural designs.

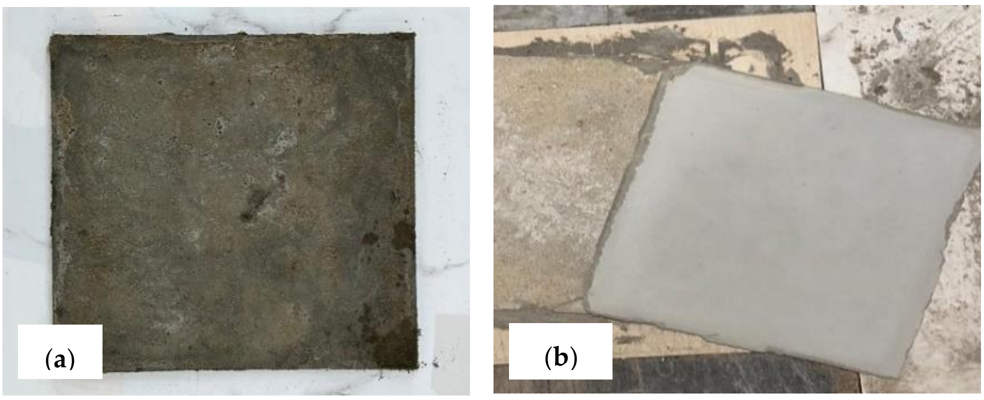

Figure 3. Cured Tiles, a. Before curing b. After curing

2.7 Testing

Compressive Strength: Tested using a Compression Testing Machine by ASTM C39 standards, as shown in Figure 4.

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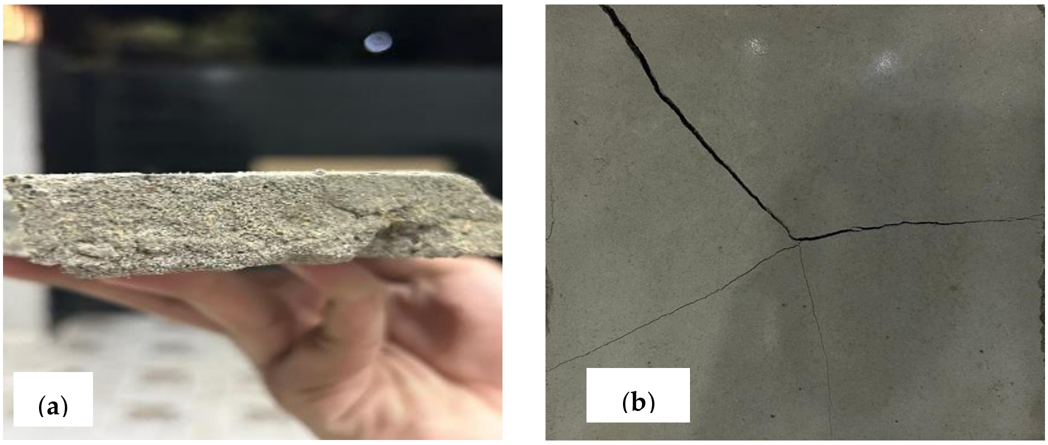


Figure 4. Tested tiles, a. Layers of aggregate b. Cracks appeared after loading

2.8 Water Absorption

Water absorption tests were conducted on the bamboo-fly ash concrete tiles to evaluate their moisture resistance and overall durability. The test followed ASTM C140/C140M standards. Specimens were dried, weighed, submerged in water for 24 hours, and re-weighed to calculate absorption as illustrated in .

Table 1.

Table 1. Water Absorption Results of Bamboo-Fly Ash Concrete Tiles

Mix ID	Bamboo Fibers (%)	Fly Ash (%)	Dry Weight (g)	Wet Weight (g)	Water Absorption (%)
T1	2	5	1950	1995	2.31
T2	4	10	1940	1998	2.99
T3	6	15	1925	1990	3.38
T4	8	20	1910	1985	3.93

All values remained below 5%, indicating that the tiles possess adequate resistance to water absorption for ceiling and roofing use.

2.9 Flexural Strength

The flexural strength of the concrete tiles was tested using the three-point bending method according to ASTM C293/C293M, as mentioned in Table 2. This evaluates the tile's ability to resist cracking or failure under bending loads, which is a key factor for roof and ceiling tiles.

Table 2. Flexural Strength of Bamboo-Fly Ash Concrete Tiles

Mix ID	Bamboo Fibers (%)	Fly Ash (%)	Tile Thickness (mm)	Flexural Load (kN)	Flexural Strength (MPa)
T1	2	5	20	0.95	2.80
T2	4	10	20	0.85	2.50
T3	6	15	20	0.78	2.30
T4	8	20	20	0.72	2.10

Although strength decreased slightly with higher bamboo and fly ash content, all mixes remained within safe limits for non-structural applications.

3. Results

The results of this study demonstrate the feasibility of using bamboo fibers and fly ash in the production of sustainable concrete tiles. The following sections present the findings for compressive strength, workability, and density.

3.1 Compressive Strength of Cylinders

Compressive strength results for the bamboo-fly ash concrete mixes are summarized in .

Table 1. The mix with 2% bamboo fibers and 5% fly ash achieved the highest compressive strength of 19.36 MPa at 28 days [10] which is shown in Table 3. This finding is particularly significant as it demonstrates that incorporating these sustainable materials can still result in concrete tiles with adequate strength for non-structural applications. The optimal combination of 2% bamboo fibers and 5% fly ash appears to strike a balance between enhancing sustainability and maintaining crucial mechanical properties. This result offers valuable insights for developing eco-friendly concrete products without compromising performance.

Table 3. Compressive Strength of Bamboo-Fly Ash Concrete Mixes

Mix ID	Bamboo Fibers (%)	Fly Ash (%)	7-Day Strength (MPa)	14-Day Strength (MPa)	28-Day-Strength (MPa)
M1	2	5	13.43	10.2	19.36
M2	4	10	10.2	12.6	18.2

3.2 Compressive Strength of Tiles

Compressive load tests were also performed on the tile specimens to examine their overall load-bearing potential, as shown in Table 4. While compressive strength is not the primary concern for tiles, this test provides useful insights into the durability and mechanical resistance of the tile matrix. The procedure was adapted from ASTM C39. This additional testing is a crucial step in comprehensively evaluating the performance of the eco-friendly concrete tiles. Even though tiles are not typically subjected to high compressive loads in their application, understanding their resistance to localized pressure or impact is vital for ensuring their longevity and functionality. By adapting a standard procedure like ASTM C39, the researchers ensure that the results are reliable and comparable to other concrete materials, further validating the potential of these sustainable tile compositions.

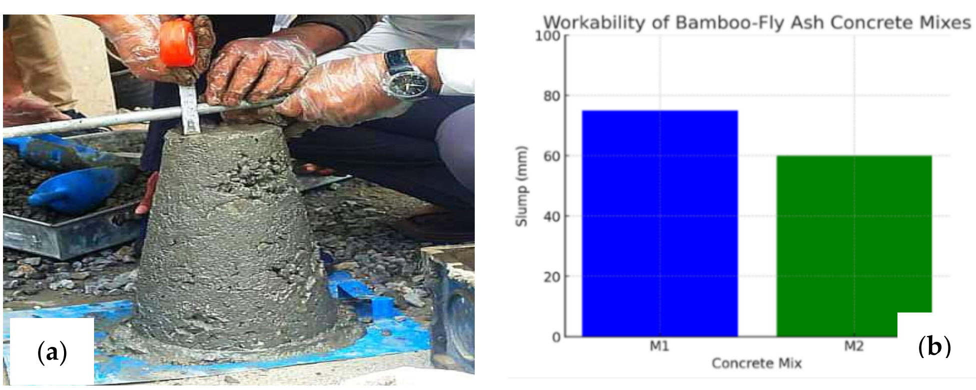
Table 4. Compressive Load Capacity of Bamboo-Fly Ash Concrete Tiles

Mix ID	Bamboo Fibers (%)	Fly Ash (%)	Tile Area (cm^2)	Load at Failure (kN)	Compressive Strength (MPa)
T1	2	5	400	7.20	1.80
T2	4	10	400	6.60	1.65
T3	6	15	400	5.80	1.45
T4	8	20	400	5.20	1.30

The tiles showed moderate compressive load capacity, sufficient for typical handling and installation loads, confirming their applicability for non-load-bearing architectural components.

3.3 Workability

The workability of the concrete mixes was assessed using slump tests. The mix with 2% bamboo fibers and 5% fly ash achieved the highest compressive strength of 19.36



MPa at 28 days for cylinders [5], and 1.80 MPa for the tiles, while the mix with 4% bamboo fibers and 10% fly ash showed reduced workability [11] as shown in Figure 5. Workability assessment of Bamboo-Fly Ash Concrete Mixes, a. Slump Test, and b. Workability comparison of different concrete mixes based on slump test results. This observation regarding workability is significant as it directly impacts the ease of placement and finishing of the concrete. While the 2% bamboo and 5% fly ash mix demonstrate superior strength, the reduced workability of mixes with higher additive percentages highlights a potential challenge. This suggests that optimizing the mix design for both strength and workability is crucial for practical applications, potentially requiring the use of superplasticizers or adjustments to the water-cement ratio to maintain flowability without compromising other desired properties.

Figure 5. Workability assessment of Bamboo-Fly Ash Concrete Mixes, a. Slump Test, and b. Workability comparison of different concrete mixes based on slump test results.

4. Practical Implementation

The findings of this study have significant practical implications for the construction industry, particularly in the development of eco-friendly and sustainable building materials [12], [13]. By replacing a portion of cement with fly ash and incorporating bamboo fibers, the proposed concrete mix offers a viable solution for reducing the carbon footprint of construction projects while maintaining adequate mechanical properties for non-structural applications such as tiles and ceilings.

The use of fly ash as a partial replacement for cement significantly reduces carbon emissions associated with concrete production, aligning with global efforts to promote sustainable construction and meet environmental regulations. The reduced density of bamboo-fly ash concrete makes it ideal for lightweight applications such as tiles and ceilings, contributing to overall structural weight reduction while enhancing durability and resistance to environmental factors. As fly ash is an industrial by-product and bamboo is a renewable resource, both materials offer cost-effective alternatives to traditional components, enabling significant savings, especially in developing countries. The optimal mix of 2% bamboo fibers and 5% fly ash demonstrated good workability, ensuring ease of handling and casting in real-world scenarios. This confirms its suitability for large-scale applications, particularly in non-structural elements. Future research should explore scaling up production and testing the material's performance in actual construction settings. Adopting this eco-friendly concrete mix allows engineers and designers to support sustainable development while maintaining structural integrity and longevity, laying the groundwork for continued innovation in sustainable construction materials.

Conclusion

This research successfully demonstrates the practical viability of using sustainable alternatives in construction materials. Through careful experimentation, we've shown that bamboo fibers and fly ash can effectively replace portions of traditional concrete components in tile production. Our findings highlight an optimal blend: the mix with 2% bamboo fibers and 5% fly ash achieved a remarkable balance of strength and environmental benefits. This specific composition yielded a compressive strength of 19.36 MPa in cylinders and 1.80 MPa in tiles, while also maintaining impressively low water absorption (<3%).

These results are significant because they offer the construction industry a tangible pathway to reduce its environmental footprint without compromising quality. The successful development of these eco-friendly tiles is more than just a technical achievement; it represents a crucial step toward reconciling essential building needs with vital ecological responsibility. By incorporating waste by-products like fly ash and rapidly renewable resources like bamboo, we can significantly lessen the demand for virgin materials and reduce carbon emissions associated with conventional cement production.While these laboratory results are highly encouraging, we recognize that bringing such innovations to market requires further dedicated work. Future studies should focus on examining the long-term durability of these sustainable concrete tiles under various environmental conditions. Additionally, exploring the challenges and opportunities associated with scaling up production will be critical for their widespread adoption. We sincerely hope this work will serve as an inspiration for both researchers and practitioners to continue developing sustainable building solutions that ultimately benefit both people and the planet.

Appendix

A.1 Raw Data

Table A1. Compressive Strength Test Results

Mix ID	Bamboo Fibers (%)	Fly Ash (%)	7-Day Strength (MPa)	14-Day Strength (MPa)	28-Day Strength (MPa)
M1	2	5	13.43	10.2	19.36
M2	4	10	10.2	12.6	18.2
M3	6	15	9.5	11.8	17.5
M4	8	20	8.7	10.5	16.3

Table A2. Workability (Slump Test) Results

Mix ID	Bamboo Fibers (%)	Fly Ash (%)	Slump (mm)
M1	2	5	75
M2	4	10	60
M3	6	15	50
M4	8	20	40

Table A3. Density Measurements

Mix ID	Bamboo Fibers (%)	Fly Ash (%)	Density (kg/m³)
M1	2	5	2300
M2	4	10	2200
M3	6	15	2150
M4	8	20	2100

A.2 *Calculations*

Calculation of Density:

As shown in Figure 6. Experimental Setup for Compressive Strength Testing, a. Specimens ready for testing, and b. Compression Testing Machine that the density was calculated using the formula:

$Density = Mass\ (kg)/Volume\ (m^3)$

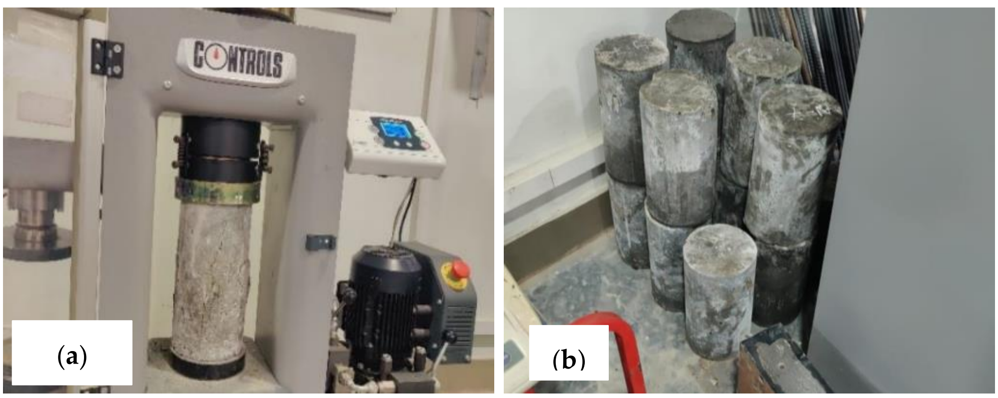


Figure 6. Experimental Setup for Compressive Strength Testing, a. Specimens ready for testing, and b. Compression Testing Machine

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