Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 10, No. 10, October, 2024

Comparative Evaluation of Compressive Strength in Earth Blocks Enhanced with Natural Fibers

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Received 11 May 2024; Revised 17 September 2024; Accepted 21 September 2024; Published 01 October 2024

Abstract

Portland cement is a key component in the production of concrete blocks; however, its production has an extensive carbon footprint that contributes towards climate change. In addition, the availability of aggregates is also often challenging and, as such, leads to production delays of concrete blocks, which ultimately causes delays in the completion of construction projects and constant price increases. The price increase of construction materials such as concrete blocks tends to affect the quality of houses being constructed in rural communities of the Pacific Island Countries (PICs), and this calls for the development of a low-cost alternative to ensure housing quality is not compromised. This project is being carried out to develop earth blocks as an environmentally friendly and sustainable substitute for concrete blocks that are widely used in the construction industry. Coir (derived from coconut fibers) and bamboo fibers were incorporated into these blocks as reinforcement materials, aiming to achieve the same level of strength required for use in construction. Additional adhesion of the earth block was provided by the usage of cement. The earth blocks were cured for 7, 14, and 28 days, after which they were subjected to various tests, including a compressive strength test, water absorption test followed by wet compressive strength test to compare its performance to ensure it has sufficient strength for it to be introduced into the market as a more eco-friendly, low-carbon-emission, and cost-effective construction material. The maximum compressive strength obtained during the test was 3.24 MPa. Following a comprehensive analysis of the data attained, the composition of 15% cement and 0.75% bamboo fiber emerges as the most ideal choice for creating marketable earth blocks. This composition strikes a balance between providing adequate strength and ensuring minimal reduction in overall strength when the blocks are exposed to wet conditions.

Keywords: Earth Blocks; Natural Fibers; Bamboo Fiber; Coconut Fiber; Compressive Strength.

1. Introduction

One of the most popular building materials used worldwide is concrete blocks, and Pacific Island Countries (PICs) are no exception because of their superior strength and ease of construction. The manufacturing of concrete blocks uses Portland cement, which is a significant component and has a high carbon footprint when made and therefore is not an environmentally conscious product. Its production also generates nitrogen oxides, sulfur, carbon monoxide, and particulate matter, leading to the contamination of water, soil, and air that has an impact on aquatic life, humans, vegetation, and animals. An estimated 10% of all energy-related carbon dioxide emissions globally in 2019 came from

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http://dx.doi.org/10.28991/CEJ-2024-010-10-013

their use, shipping, production, and destruction [1, 2]. Other materials, such as high-quality aggregates, can also be challenging to find at times, particularly in the Pacific islands, which causes production delays. Additionally, a study by the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) revealed that the standard of homes built in remote Pacific Island communities tends to suffer because of the increasing cost of building materials. Several nations, including Fiji, experience worsening conditions because of natural disasters like hurricanes and floods [3]. Hence, there is a crucial requirement for a sustainable and environmentally friendly alternative to decarbonize the manufacturing sector of the construction industry in the region. Thirty percent of people on our globe now reside in earthen homes. Earth blocks are used extensively because they are inexpensive, readily available, and have a long history of usefulness. The need for affordable housing for all is an important aspect in today's time. High costs for labor, materials, and transportation have made it difficult for some people to live even in developed areas. Mud or earth blocks, commonly known as adobe or earthen blocks, are a type of building material made primarily from a mixture of in-organic sub soil, non-expansive clay, sand, and aggregates and have been used as a fundamental building material for centuries. The use of earthen blocks is deeply rooted in various cultures globally, and due to their eco-friendly nature, affordability, and abundant availability of raw material makes earthen blocks a sustainable alternative to conventional construction material.

One of the major drawbacks of the use of earthen blocks is the limited load-bearing capacity. The compressed earth blocks have low compressive strength of about 2 to 3 MPa and are mainly used in the construction of only one-story buildings [4]. In the Pacific, many countries, such as Fiji, Samoa, Kiribati, and many more, utilize small, single-story houses, especially in the rural communities. This study therefore investigates the properties of earthen blocks by understanding and optimizing the properties to ensure structural integrity and longevity in the construction industry. This comparative analysis aims to explore the effects of reinforcing mud or earth blocks with natural fibers on their compressive strength. Numerous studies have reported on the compressive strength of earthen blocks reinforced with natural fibers [4-8]. Mostafa and Uddin [4] experimentally studied the influence of banana fiber length on the flexural and compressive strengths of compressed earth blocks. It was seen that the fiber properties had a significant effect on the strengths of earth blocks, such as fiber percent, length, fiber surface conditions, and production method. They studied several material property combinations and found out that the best forming combination was the fiber length of 50 mm and fiber percentage of 0.35 by weight while assessing flexural and compressive strengths. The compressive strength increased from 3.33 MPa to 5.92 MPa, showing a significant increase in compressive strength of 78% with the addition of banana fibers in the compressed earth blocks.

Danso et al. [5] conducted a study whereby it was concluded that adding 0.5% of coconut fiber to high clayey soil and low clayey soil blocks boosted their compressive strength by about 41% and 57%, respectively, as compared to unreinforced blocks after 28 days of curing time. This was due to the flexible fiber-forming mesh within the soil structure, which strengthens the bond holding the block together. A comparable study was conducted by Thanushan et al. [6], where the coconut fiber-reinforced matrices were produced with fiber at 0, 0.2, 0.4, and 0.6% mass fractions of cement and soil mix while the water–cement ratio was kept at 0.9. The results showed that fiber reinforcement significantly increases the energy absorption, ductility, toughness, and residual strength. The samples were tested for 7, 14, and 28-day curing periods, and based on the test results, the maximum strength was obtained after it had been left to cure for 28 days and had a fiber content of 0.4%. Further, Kasinikota and Tripura [7] presented that the addition of coir fibers to compressed stabilized earth block masonry panels modified the failure behavior from brittle to more ductile. The addition of coir fibers to grouted masonry earth prisms enhanced the compressive strength by 40% because the additional fibers acted as bridges and resisted the tensile stresses that formed in the matrix, stopping the spread and extension of cracks in blocks. According to Bourki et al. [8], in their summary of the mechanical properties, coconut fiber has the highest mechanical strength of all the tested fibers (coconut fiber, wheat straw, crop straw, and wool); in fact, its tensile strength reaches 174 MPa, and its elastic modulus ranges from 19 to 26 GPa. Natural fibers' high cellulose content guarantees good tensile and flexural strengths.

Paul et al. [9] studied the influence of areca fiber (0 to 3%) and cement on the engineering characteristics of compressed stabilized earth blocks. The areca palm, or Areca catechu, is a tropical plant that grows well in East Africa, Asia, and the Pacific. The fibers obtained from areca nutshells, which are frequently considered agricultural waste, offer a promising material for sustainable construction practices. Areca fiber-reinforced earth blocks exhibited increased split tensile strength, compressive strength, and flexural strength and optimized water absorption rates. One noteworthy discovery is that a 2 percent areca fiber content was found to be ideal, resulting in major increases in durability and strength values. The benefits of a 2 percent fiber content were further validated by microstructural investigation using scanning electron microscopy (SEM), which revealed a compact and cohesive interior structure with fewer voids and cracks. The improved stability and bonding that the areca fibers offer is highlighted by this microstructural integrity. Moreover, Paul et al. [10] evaluated the vetiver straw fibers' suitability for enhancing earth bricks' engineering properties. In terms of strength characteristics, it was discovered that adding vetiver straw fibers did not greatly increase dry unconfined compressive strength and occasionally had an adverse effect, especially at 1.5% fiber content. After 7, 14, and 28 days of drying, the compressive strength of the Vetiver straw fibers-reinforced samples ranged from 0.734 to 1.099 MPa, 0.791–1.229 MPa, and 0.904–1.362 MPa, respectively.

Kolawole et al. [11] utilized bamboo fibers and stated that the compressive strength of bamboo-reinforced laterite (soil rich in iron oxide and derived from a wide variety of rocks) blocks increased from 2 MPa to a maximum of 5 MPa for 0 to 25% bamboo fiber addition to laterite soil blocks. Additionally, the sample that contained 25% bamboo fiber had a flexural strength and fracture toughness of 1.70 and 2.25 MPa, respectively. The water absorption of the sample earth block without bamboo fiber had a minimum water absorption of 6%, and samples with 25% of bamboo fiber had a maximum water absorption of 11.4%. The addition of bamboo fibers to laterite soil has shown a significant increase in fracture toughness because the fibers act as a reinforcement, improving the material's ability to resist crack propagation and absorb energy. The combination of earth and bamboo creates a material that is resistant to weather, moisture, and pests, and has a high load-bearing capacity. This makes bamboo earth blocks an ideal choice for building structures in areas with high seismic activity, as they can better withstand the forces of earthquakes and other natural disasters [12]. A similar study was conducted by Mbereyaho et al. [13], where they used bamboo fiber to reinforce earth blocks with 8 different sizes of fiber ranging from 10 to 100 mm. The results revealed that while the water absorption of the sample earth block with bamboo fiber varied from 6 to 9%, the highest compressive strength of the earth block with bamboo fiber reinforcement was 4 MPa. The mechanical properties for earth blocks with reinforced bamboo fiber in these studies did not vary much, which shows that the bamboo fiber is quite suitable to be incorporated into earth blocks as a reinforcement. As such, they can be used for a variety of purposes because they have a minimum acceptable strength, particularly for straightforward wall structures, and they are also reasonably priced and environmentally friendly. Several studies have shown the effective use of bamboo and bamboo fibers in enhancing the performance of concrete structures; however, there is limited research on bamboo-reinforced earth blocks in the literature [14-16]. In terms of concrete strength, bamboo fibers exhibit encouraging results and prevent inevitable brittle failure. This has motivated the authors to conduct the comparative analysis of earth blocks reinforced with bamboo and coir fibers.

Subramanian et al. [17] studied the water absorption of natural fiber-reinforced earth blocks. The water absorption of blocks reinforced with banana fiber varied from 10% to 20%, whereas blocks reinforced with coconut fiber had a minimum of 15%, and the values rose as the amount of fiber increased. With 5% cement, the maximum water absorption for palm fiber blocks was 12%, whereas the maximum water absorption for cassava peels was 28%. An important factor is also the compaction pressure used when the block is being produced. The density, compressibility, mechanical strength, porosity, and permeability of the block are all impacted by the amount of compacting pressure applied. All these factors have an impact on the blocks' overall water absorption as well as the kind and composition of the fiber, including its cellulose content. Thanushan et al. [6] showed that the wet density of coir-reinforced earth blocks was higher compared to the dry density. The absorbent nature of coconut fiber (which has a greater water absorption rate of 145–209% [5] compared to the soil water absorption rate) and void volume in the mix are the two key variables influencing higher wet density for earth cement blocks with coconut fiber. Soil achieves maximum dry density when compacted at ideal moisture content, crucial for determining its dry compressive strength. However, strength decreases when saturated with water, requiring a stabilizer. Stabilizers, like Portland cement, play a vital role in bonding soil-stabilizer mixes, reducing soil swelling, and enhancing strength and durability in earth blocks [18]. Compressive strength and cement content show a high, often linear association, used to determine optimal cement content for reinforcing earth blocks with bamboo and coconut fiber. Soil with a plasticity index below 15 is suitable for cement stabilization, typically with 4-10% cement added to the soil's dry weight [19]. Blocks with less than 5% cement can be too friable for easy handling [20].

A study conducted by Waziri et al. [21] demonstrated that increasing cement content improves earth block strength. In their study, blocks with 7.5% cement content had the highest strength (2.48 MPa) after 28 days of curing, with strength increasing with higher cement content, averaging 0.35 MPa. In addition, a similar experimental work was conducted by Namango et al. [22], whereby the earth blocks were experimented with sisal fiber reinforcement using cement as a binder. Cement varied from 5% to 12% of soil weight. Non-fiber blocks with 9% cement had 2.96 MPa compressive strength, while 12% cement yielded 3.24 MPa. Sisal fiber content ranged from 0.25% to 1.25%. With 0.5% fiber and 12% cement, the block achieved a significant compressive strength of 6.98 MPa after 28 days, highlighting the combined strength contribution of cement and good adhesion between soil and fibers. For maximum strength, stabilized soil blocks need damp curing, crucial for cementitious materials. If exposed, blocks can develop shrinkage cracks due to moisture loss. To prevent this, blocks can be covered with a damp cloth or plastic bag or misted with water regularly. Maintaining an ideal curing room temperature of 25±5℃ and avoiding sunlight exposure in the initial days are recommended measures [23]. Optimizing fiber types and ratios is important. The impact of varying natural fiber types and ratios on the compressive strength of earth blocks has not received much attention. It is essential to know which fibers, and in what ratios, provide the optimal strength-to-durability ratio [24]. Compressed earth blocks' main drawbacks are the tendency to swell and erode when exposed to moisture or rain and their low compressive strength. This study aims to strike a balance between incorporating minimal amounts of cement and integrating natural fibers to enhance the performance of compressed earth blocks. We seek to improve their resistance to water absorption, as well as to boost their compressive strength, while maintaining the ecological and economic benefits of using both natural and sustainable materials. In general, the significance of this study is in the threefold way it overcomes the above-said disadvantages. Firstly, this study focuses on establishing the strength characteristics of earthen blocks derived from clay soil, which is readily available in the Fiji Islands, which is novel in Fiji's context. Secondly, the study comparatively analyzes the use of coir and bamboo fibers as reinforcements and the use of cement as a binding agent. Lastly, the study seeks to contribute valuable insights in the field of eco-friendly construction materials and techniques in the Pacific, where natural resources are scarce, therefore aiding policymakers to develop and implement codes on the use of alternative resources for infrastructural development. The remainder of this paper is structured as follows: Section 2 discusses the study area and provides the map of the area. Section 3 outlines the research materials and methodology, including material preparation, sample preparation, mix ratios, and tests conducted. Section 4 presents the results of this study and a discussion of the findings, and section 5 concludes the study, offering implications, limitations, and suggestions for future research.

2. Study Area

The Fiji Islands is a Melanesian group of islands in the South Pacific, between latitudes 15° South and 21° South and straddling the 180th meridian from 177° West to 175° East. Located strategically in the South Pacific Ocean, Fiji spans an area of about 2,000 kilometers' northeast of New Zealand, comprising over 300 islands with diverse geographical features. The archipelago, divided into the larger Viti Levu group and the Vanua Levu group, offers varied environmental conditions, making it an ideal setting for studying natural fiber-reinforced earth block applications. Fiji's islands range from large landmasses, such as Viti Levu and Vanua Levu, to smaller islets, each contributing to a unique topography and soil composition.

The geographical diversity extends to the climate, characterized as tropical maritime, with distinct wet and dry seasons. Abundant rainfall, tropical temperatures, and exposure to oceanic influences contribute to the dynamic ecosystem and geological processes shaping the islands. The rich biodiversity, including rainforests, mangrove swamps, and coral reefs, further influences soil composition and the overall environmental context. This dynamic tapestry of islands, terrains, climates, and ecosystems provides the backdrop for our research, addressing the challenges and opportunities presented by Fiji's unique environmental conditions. Examining Fiji's geological history near the Australian–Pacific plate boundary reveals an intricate narrative. The western part of Viti Levu contains island-arc volcanics dating back 56-34 million years. Tectonic shifts over time led to the formation of more volcanic islands and sedimentary basins. Viti Levu, the first major landmass, emerged 16 to 5 million years ago, followed by Vanua Levu (7 million years ago) and Taveuni (less than 2.5 million years ago). This complex history influences soil formation. Acidic parent materials with high silica and low ferromagnesium mineralogy result in resistant, low-clay-content soils. Basic parent materials, with lower silica but higher ferromagnesium minerals, produce easily weathered, clayey, and fertile soils. Sedimentary composition depends on the original rock and weathering when parent material is "reworked," with sandstones tending to be silicious and limestones, calcareous tuffs, and marls being more intermediate or basic. Fiji's soil-forming parent materials include acid volcanic rocks, siltstones, sandstones, crystalline rocks, coral limestones, marls, basic volcanic rocks, and various transported materials. Tuffaceous sedimentary rocks (36% of the landscape) and basic volcanic rocks (48% of the landscape) are the major parent material groups [25]. The study area is located at Fletcher Road, Laucala Bay, which is situated in Suva, Fiji, at the coordinates approximately 18°08'25.7"S and 178°27'23.8"E longitude as shown in Figure 1. Fletcher Road is a vital transportation artery within the industrial district of Suva, located near the industrial area and stadiums and characterized by heavy vehicular traffic.

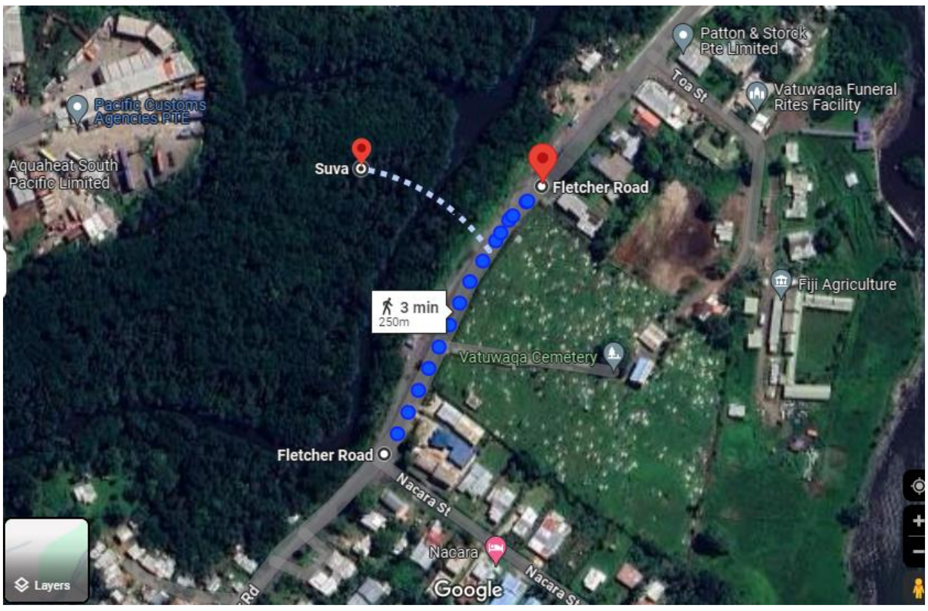

Figure 1. Map of study area [26]

3. Materials and Specimens Preparation

Coconut fibers and bamboo fibers are used in this study. Extracted from the outer shell of the coconut, coconut fiber serves as a great structural component and is sturdy, long-lasting, fungus- and moisture-resistant, moth-proof, and unaffected by dampness. Global production of coconut fibers is estimated to be around 500,000 tonnes per year. When coconut fibers are extracted, half of them are wasted [27]. The main constituents of coconut fibers are cellulose, hemicellulose, and lignin. The various characteristics of coconut fibers are influenced by these components. Coconut fiber has a tensile strength of approximately 107-174 MPa, an ultimate elongation of 24%, and a toughness of 14 MJ/m^3. Since ancient times, buildings have frequently been constructed from bamboo, a natural resource [14]. Because of its high tensile strength-to-weight ratio, greater availability, low cost, exceptional flexibility, renewability, and environmental friendliness, bamboo can be a desirable alternative to reinforcing steel [15]. Several studies have been conducted to assess bamboo's potential as a steel substitute in structural parts [14–16]. However, there has only been a few research on the use of bamboo as an internal reinforcement material for brick walls made of adobe and CEB. Bamboo fiber has a tensile strength of approximately 324 MPa, elastic modulus of 21286 MPa, and a compressive strength of 92 MPa [7].

3.1. Coconut Fiber Extraction

Using a sharp knife, the husk was separated from the shell, after which the husks were sun-dried for 3 days for easy fiber removal. The fibers were carefully removed from the outermost skin while ensuring that the fibers did not break during the extraction process. By stripping the extracted fibers, individual fiber strands were obtained and cut into a uniform length of 50 mm (Figure 2).

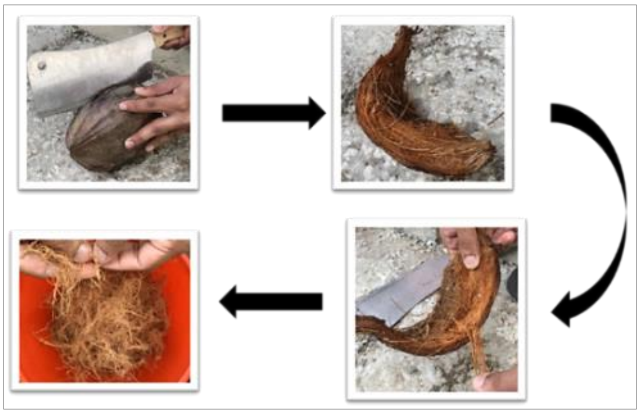

Figure 2. Coconut fiber extraction process

3.2. Bamboo Fiber Extraction

Bamboo was cut into small pieces and its outer skin was removed before letting it soak in a solution of NaOH (caustic soda) for 2 days. This solution helps to minimize the starch content within the bamboo as well as to prevent fungal and insect infestation. After removing the bamboo from the solution, it was beaten with a mallet to smoothen it for easy extraction. Individual fibers were then manually separated from the bamboo pieces and cut into lengths of 50 mm for consistency (see Figure 3).

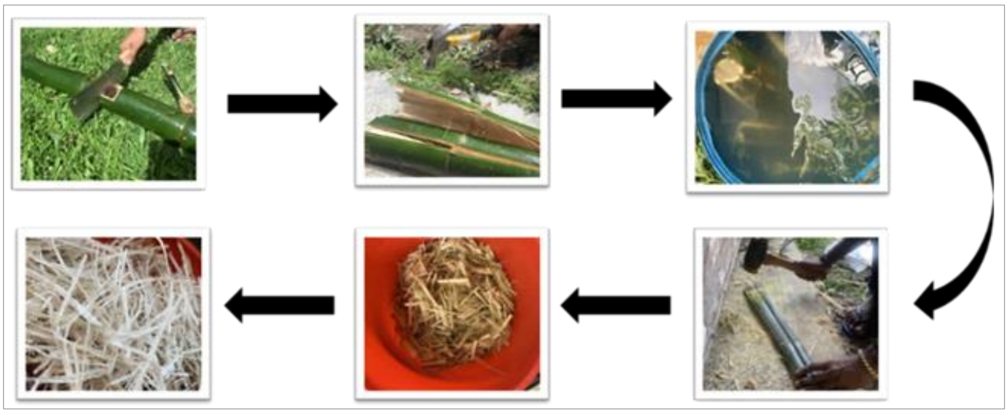

Figure 3. Bamboo fiber extraction process

3.3. Preparation of Test Samples

Soil was firstly oven dried to remove moisture, after which the clumps of soil were broken into finer pieces. A sieve was used to remove rocks and other debris that were mixed with the soil. An earth block sample was prepared without any fiber reinforcements and binder content, and it was determined that the mass of soil required for each sample was 1.2 kg. The clay soil used had an OMC of 20%, but since cement was used as a binder, the water content increased to 25% to allow for adequate workability of the soil-cement-fiber mix. Once the required soil-cement-fiber mix was prepared, it was then placed in a plastic mold measuring 100 x 100 x 100 mm. This dimension was chosen because of the limitation of the compressive strength testing machine. The mix was placed layer by layer, and after placing each layer, it was manually compacted using a rammer weighing 5 kg. The bricks were cured in 3 stages. After molding, the mud bricks underwent an initial drying phase prior to being fully cured. The samples were air-dried in a shaded room whose temperature was regulated to 27°C. The samples were air-dried for a period of 2 days to allow excess water to evaporate. Once the bricks were hard enough to withstand deformation during handling, the molds were removed, and the bricks were placed in a cool room covered with a damp cloth to avoid rapid drying, as this would cause shrinkage, which would therefore lead to crack formation on the surface of the sample. The samples were left to cure for a period of 7, 14, and 28 days, respectively (Figure 4). After the respective curing days, the samples were subjected to compressive and water absorption tests. The mix ratios in this study are shown in Table 1.

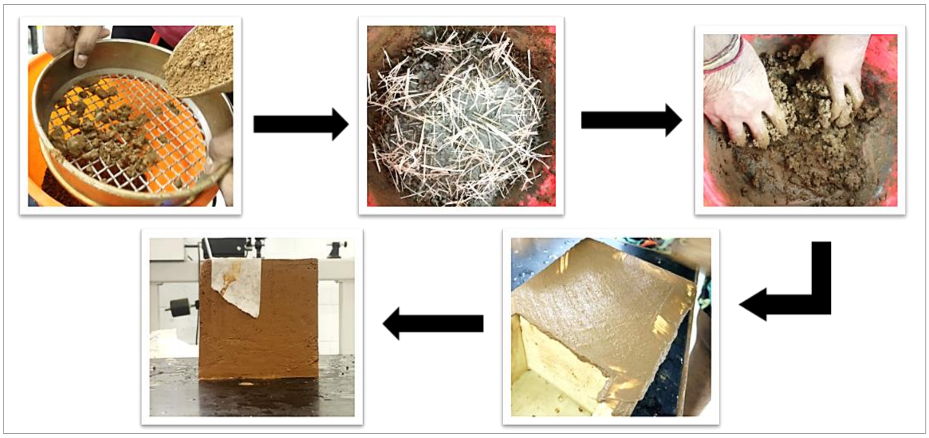

Figure 4. Sample preparation

Table 1. Mix ratios

Sample	Fiber percent (by weight)	Cement percent (by weight)	Clay soil
Control sample	0	0, 5, 10, 15	1.2 kg per sample
Bamboo fiber	0.5, 0.75, 1	5wt.% - added to each fiber set, similarly, 10wt.% is added to each fiber set and 15wt.% is added to each fiber set	
Coconut fiber (coir)	0.5, 0.75, 1		

Earth blocks of 100 × 100 × 100 mm were subjected to a concentrated loading as shown in Figure 5. Crushing failure was observed as the primary failure mechanism of the samples. As the load increases, elastic deformation was observed. Microcracks started from the outside of the material structure, and this may be attributed to the clay material's inability to withstand stress. Furthermore, signs of shear stresses were observed to form along the corners of the sample and propagate diagonally, which led to a partial collapse prior to complete failure as shown in Figure 5. The findings also imply that the fibers have an impact on the brittleness of the matrices. In every case, the unreinforced samples showed abrupt failure. The capacity of fibers to bridge microcracks is correlated with an increasing aspect ratio, according to earlier research [4-6]. Tensile stress from the rupture section is transferred to the fibers at the crack zone.

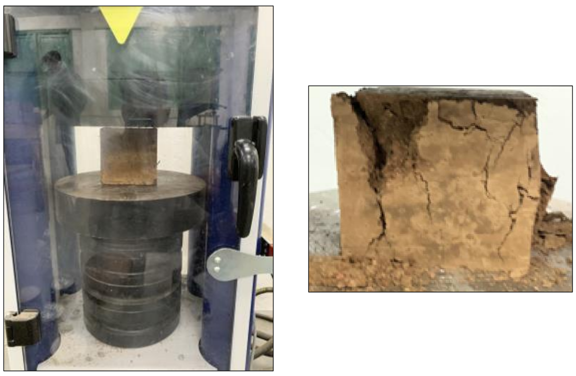

Figure 5. Compression test set-up and broken sample

4. Results and Discussion

Tests were conducted to determine the geotechnical properties of the soil for making earth blocks. A critical assessment identified the Optimum Moisture Content (OMC), crucial for soil compaction. The OMC, found to be 20% as shown in Figure 6, indicates the moisture level at which the soil achieves maximum density for a robust foundation. The OMC represents the soil's mass per unit volume without moisture. The maximum dry unit weight was determined as 11.92 kN/m³, representing the highest achievable mass under ideal compaction conditions. To ensure optimal compaction, it's essential to maintain moisture content within a specified range of 11.5% to 20.5%, ensuring the soil attains the necessary strength and stability for construction projects [15, 28]. The water content of the mix ratios was managed and kept close to the ideal moisture content as feasible to obtain the best compaction. This made it possible to achieve the highest dry density possible with the appropriate applied load. The Atterberg Limits test determined the liquid limit (LL) and plastic limit (PL) of the soil. The liquid limit, as seen in Figure 6, at 34.18%, signifies the moisture content where the soil behaves like a liquid, flowing under its weight. The plastic limit, calculated at 37.81%, is crucial for assessing soil plasticity and workability. These limits offer insights into the soil's engineering behavior, guiding decisions on its suitability for different applications. California Bearing Ratio (CBR) values indicate soil bearing capacity and strength. A CBR of 12.71% at 2.5 mm penetration depth suggests moderate strength, but at 5 mm, it drops to 10.83%, indicating reduced capacity and potential deformation under heavier loads as seen in Figure 7. CBR values below 15% are considered weak, requiring additional support or reinforcement for heavy loads. These data are crucial for understanding soil strength and geotechnical properties, informing the creation of workable earth block samples with cement and fiber incorporation.

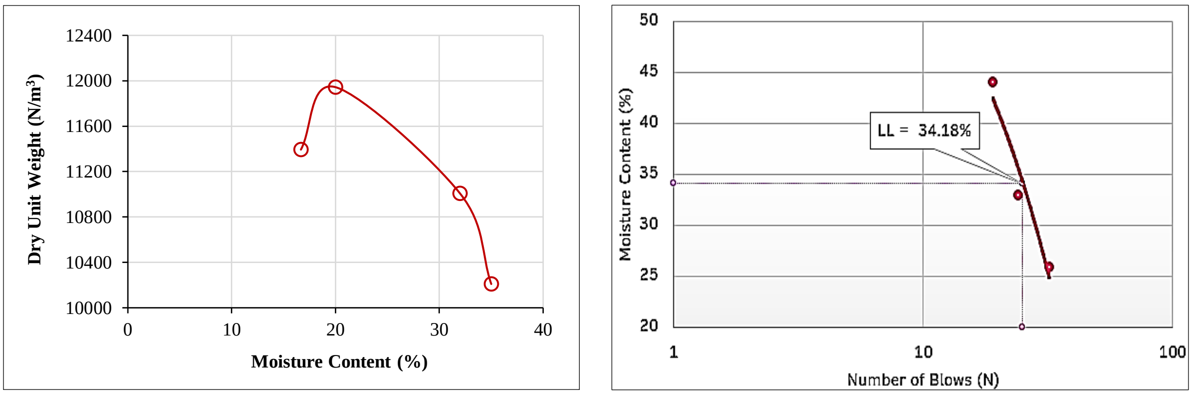

Figure 6. Moisture weight curve and moisture content against number of blows

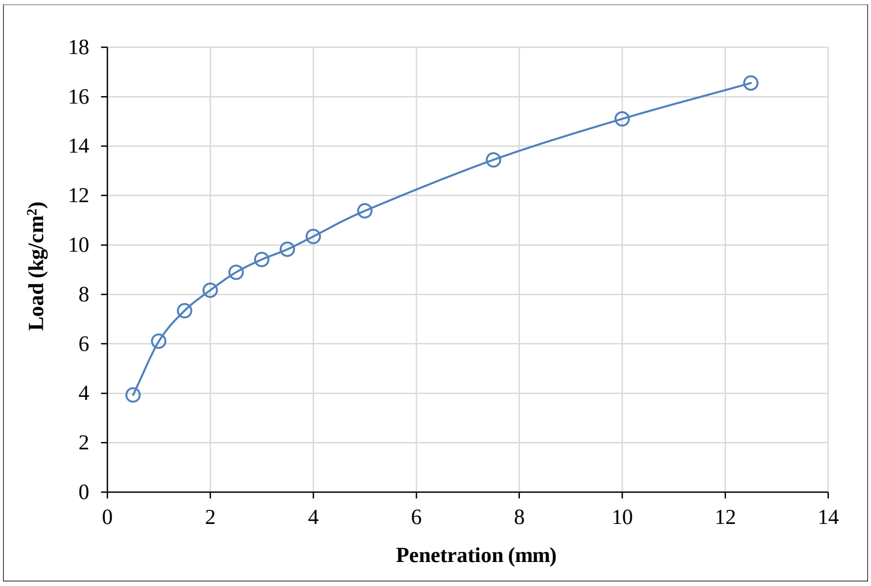

Figure 7. Axial load against penetration

Samples were subjected to compressive strength tests after 7, 14, and 28 days of curing to assess the impact of different fiber and cement content on block strength. The baseline sample, without fiber or cement, had compressive strengths of 0.06 MPa, 0.064 MPa, and 0.07 MPa for 7, 14, and 28 days, respectively. Soil-cement samples with varying cement content (5%, 10%, 15%) were compared against fiber-reinforced samples (0.5%, 0.75%, 1%) using coconut and bamboo fibers. The samples for the compressive strength tests were tested according to ASTM International C67-07. It can be seen from Table 2 that a maximum compressive strength was obtained for blocks containing 15% Portland cement cured for 28 days. Compressive strength increased by 96% when the cement content was increased from 0 to 15%. Further, the compressive strength for 15% cement contact increased by 47% from 7 days of curing time to 28 days of curing time. Ettringite, calcium silicate hydrates, and calcite can also form when cement is added to clayey soil [24]. The soil particles will have fewer pores in a more uniform microstructure due to these calcium silicate hydrate forms. This in turn increased the compressive strength of the cement-stabilized earth blocks. According to Zhang et al. [29], the porosity can decrease by 2-3 times when cement is added to clayey soil. Moreover, the effect of curing days is negligible on the clay soil earth blocks compressive strength made without any Portland cement content. On the other hand, the effect of curing days was evident for samples containing cement. According to Raj et al. [27], the bonding of surface-active particles, like clay, within the soil and the creation of a cement gel matrix that holds the soil particles together give cement-stabilized soil blocks their strength. In certain cases, if less cement is used for stability, the compressive strength may drop. A study by Raj et al. [27] and Minke [30] discovered that a very small amount of cement content (2%) can reduce the strength. Previous studies have shown higher compressive strength of unreinforced soil compared to the findings of this study: 1.21 MPa [27], 0.534 MPa [31], 1 MPa [32], and 0.45 MPa [33]. Moreover, the compressive strength found for the clay soil stabilized with 10% cement is as follows: 7 MPa [34], 2.42 MPa [24], 3.3 MPa [35], and 3.15 MPa [36].

Table 2. Compressive strength of samples without any fiber reinforcement

Composition	Average Compressive Strength (*MPa*) 7 days curing	Average Compressive Strength (*MPa*) 14 days curing	Average Compressive Strength (*MPa*) 28 days curing
Clay soil earth blocks	0.06	0.06	0.07
Clay soil with 5% cement earth blocks	0.13	0.36	0.49
Clay soil with 10% cement earth blocks	0.54	0.61	0.72
Clay soil with 15% cement earth blocks	0.83	1.16	1.58

Results in Figure 8 show that adding 5% cement and fiber significantly increases compressive strength of earth blocks after 7, 14, and 28 days of curing. Bamboo fiber-reinforced blocks reached a maximum strength of 0.50 MPa after 7 days, a substantial improvement over unreinforced block at 0.13 MPa. Coconut fiber-reinforced blocks showed higher strength (0.66 MPa) than bamboo with the same fiber and cement composition. Both fiber types demonstrated increased strength with higher fiber content. Extending curing to 14 days further improved the strength for both blocks. Bamboo-reinforced blocks achieved 0.69 MPa, while coconut-reinforced blocks showed significant strength changes with varying fiber content, reaching a maximum of 0.85 MPa. After 28 days, bamboo-reinforced blocks reached 0.88 MPa, same as coconut-reinforced blocks of 0.88 MPa. In comparison, unreinforced blocks had a strength of only 0.49 MPa, highlighting the benefits of fiber reinforcement. Increasing cement from 5% to 10% moderately boosted earth block strength (Figure 9). In the 7-day curing period, coconut fiber-reinforced blocks performed like bamboo fiber counterparts, showing strengths from 0.72 MPa to 1.36 MPa. This was not the case for 5% cement content blocks which showed that coconut fiber-reinforced earth blocks outperformed bamboo fiber-reinforced earth blocks. Coconut/bamboo fiber demonstrated better early strength of 0.72 MPa which reached up to 1.36 MPa compared to the unreinforced sample at 0.54 MPa. After 14 days, fiber-reinforced blocks maintained higher strengths in the range of 0.82 MPa to 1.59 MPa for fiber content in the range of 0.5 to 1%, respectively.

These strengths further improved after 28 days of curing. There is a significant difference in the strength of coconut fiber-reinforced blocks (0.96 MPa to 1.64 MPa) when compared to bamboo-reinforced blocks (1.20 MPa to 2.06 MPa). The compressive strength of unreinforced blocks with 10% cement content is 0.72 MPa. Increasing cement to 15% was observed for 7, 14, and 28-day curing periods given in Figure 10. At 7 days, bamboo-reinforced blocks showed superior strength (2.13 MPa at 1% fiber content) over coconut-reinforced blocks at 1.63 MPa and unreinforced blocks at 0.83 MPa. After 14 days, coconut-reinforced blocks reached 1.84 MPa, but bamboo-reinforced blocks surpassed at 2.49 MPa, a 26.1% increase. Unreinforced blocks reached only 1.16 MPa. After 28 days, coconut-reinforced blocks peaked at 2.64 MPa, a 38.3% increase, while bamboo-reinforced blocks achieved the highest strength at 3.24 MPa, a substantial 34.3% increase from 7 days and notably higher than unreinforced blocks at 1.58 MPa. Both coconut and bamboo-reinforced blocks benefited from longer curing periods, with 15% cement content maximizing strength, though bamboo mainly outperforms coconut in many cases. It is seen that bamboo fiber is a more effective strengthener of the earth blocks when compared to coconut fiber after longer curing period of 28 days and at higher cement content of 10% and 15%. A single bamboo fiber can have tensile strengths and moduli of about 1.43–1.69 GPa and 32–34.6 GPa, respectively, with an elongation of 4.3–9.7% at break. Bamboo fiber is classified as natural glass fiber because of these characteristics [37]. Bamboo fibers exceptional mechanical performance and distinctive qualities have drawn a lot of interest in the manufacturing of fiber-reinforced composites materials [38, 39].

The modulus of elasticity of coconut fiber is 681.4 MPa, failure strain is 22.4%, and average tensile strength is 130.9 MPa [40]. There are more advantages when mechanical and chemical stabilization are combined. To stop soil particles from reorienting and flocculating, which in turn stops the creation of expanded pores and fractures, it helps bind soil particles together and fill soil pores. Raj et al. [27] reported that as the fiber content was increased up to 0.8%, the compressive strength of coconut fiber earth blocks increased by 87%, this content was deemed optimal since the compressive strength began to decline beyond this threshold. In another study by Sri Bhanupratap Rathod & Venkatarama Reddy [41], it was seen that the optimal strength was obtained for 1% coconut fiber with 10% cement stabilized earth blocks. An increase up to 15% in strength was seen with this combination. Moreover, it is reported that the compressive strength is enhanced by 30% when compared to 2% coconut fiber and 7 % cement combination. It can be said that the cement stabilization strongly influences the optimal fiber content in the process of optimizing compressed earth blocks mechanical properties.

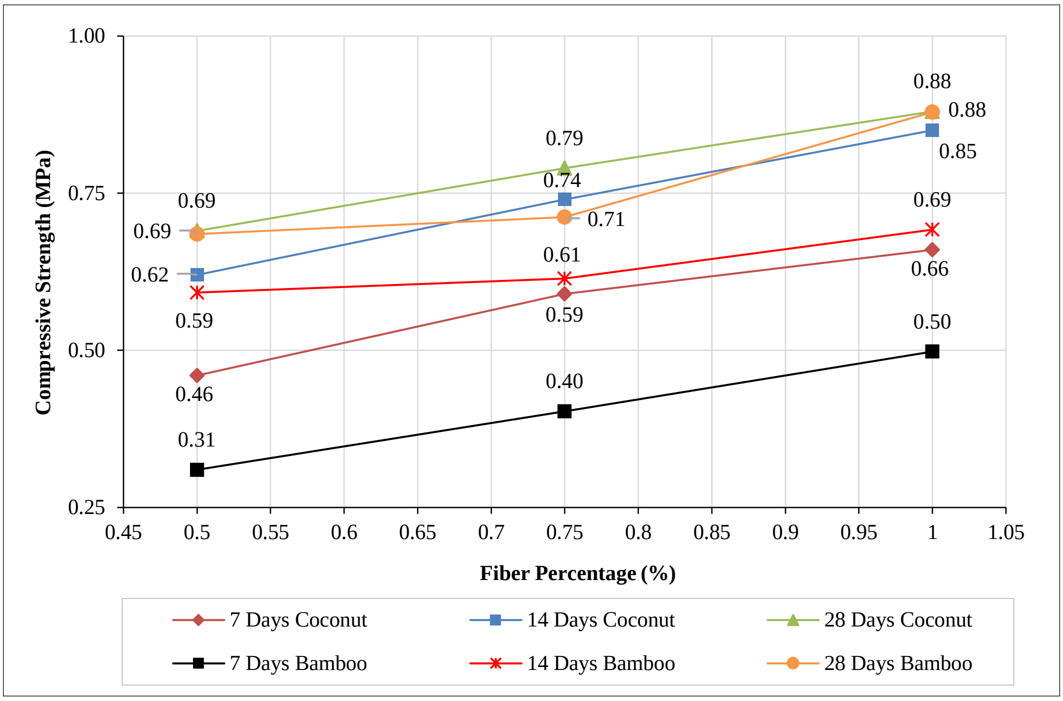

Figure 8. Compressive strength of fiber-reinforced blocks containing 5% cement as a binder

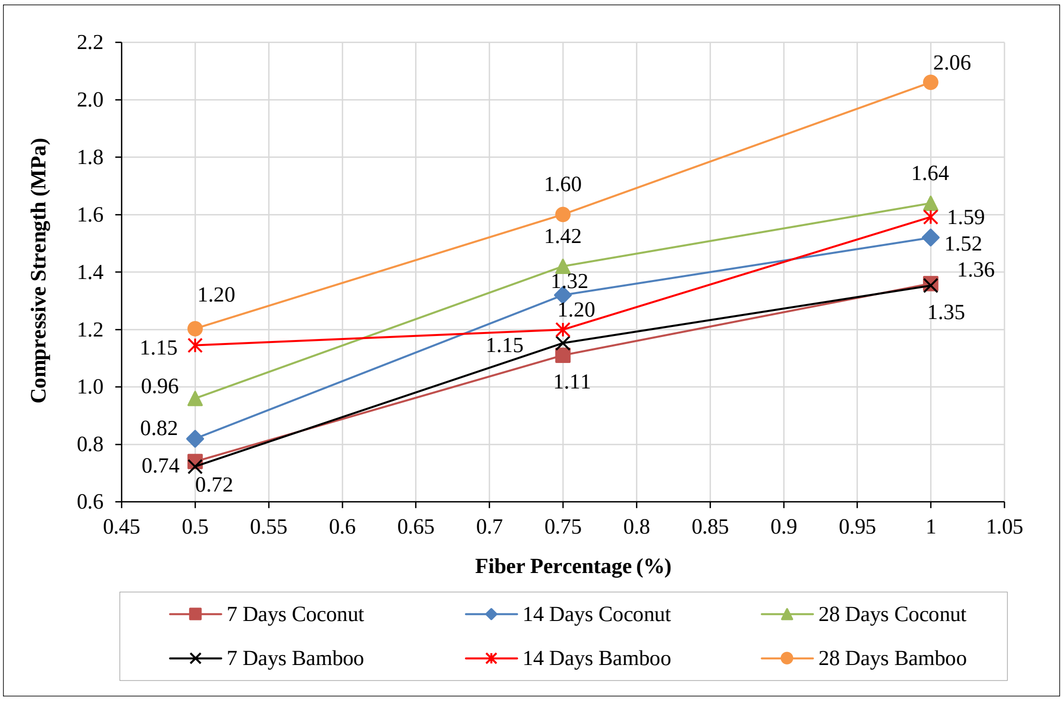

Figure 9. Compressive strength of fiber-reinforced blocks containing 10% cement as a binder

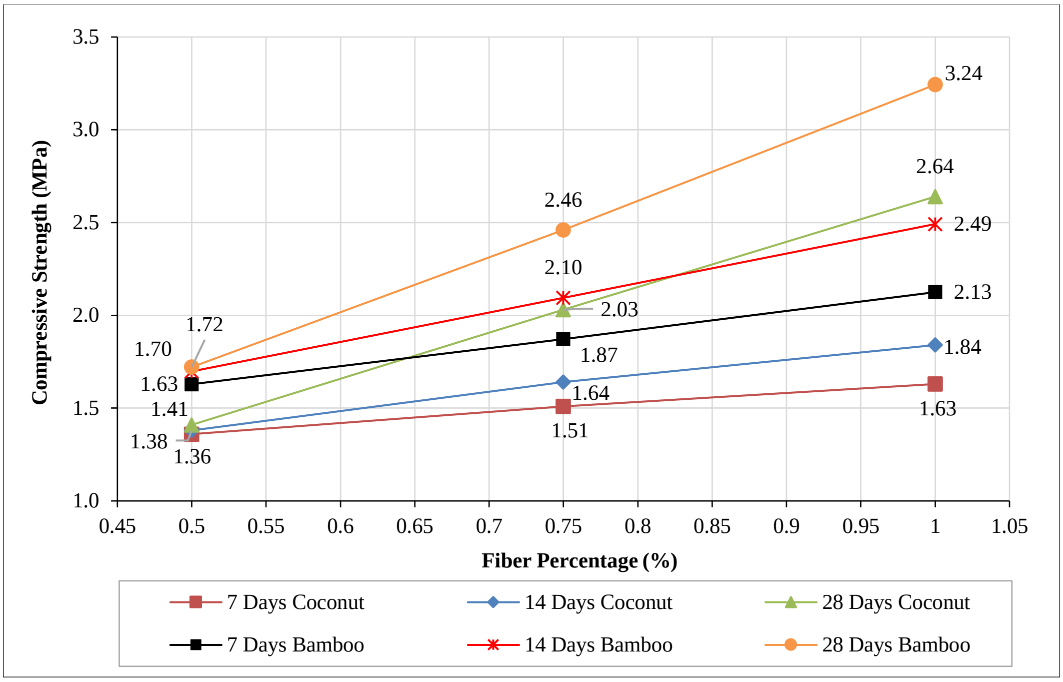

Figure 10. Compressive strength of fiber-reinforced blocks containing 15% cement as a binder

An accurate assessment of the material's water resistance and, consequently, the longevity of the construction structures can be made by determining the water absorption capacity, which is a crucial parameter. The porosity and density of the material have an impact on its ability to absorb water. To assess porosity and moisture absorption of earth blocks, a water absorption test was conducted following ASTM D570 standards. The dry weight of samples was measured, and then they were submerged in 22℃ water for 24 hours. Afterward, the wet weight was measured after wiping with a dry cloth, and the percentage of water absorbed was calculated (using equation 1), as shown in Table 3. This test helps determine the block's water resistance and its suitability for construction applications.

$$\%\ \text{water absorbed} = \frac{Dry\ weight - Wet\ weight}{Dry\ weight} \times 100 \tag{1}$$

Table 3. Water absorption results of fiber-reinforced earth blocks

Fiber	Cement Content	Fiber Content (%)	Water Absorption (%) 7 days curing	Water Absorption (%) 14 days curing	Water Absorption (%) 28 days curing
Coconut fiber	5	0.5	3.6	3.6	1.5
Coconut fiber	5	0.75	4.4	4.4	2.2
Coconut fiber	5	1	2.1	3.5	3.4
Coconut fiber	10	0.5	2.8	3.6	2.2
Coconut fiber	10	0.75	2.1	1.4	2.3
Coconut fiber	10	1	1.4	4.2	2.2
Coconut fiber	15	0.5	0.7	1.4	0.7
Coconut fiber	15	0.75	1.4	1.4	1.4
Coconut fiber	15	1	0.7	1.4	2.7
Bamboo fiber	5	0.5	3.6	4.3	2.9
Bamboo fiber	5	0.75	2.8	2.8	2.1
Bamboo fiber	5	1	4.3	2.2	2.8
Bamboo fiber	10	0.5	2.1	2.9	2.2
Bamboo fiber	10	0.75	4.3	2.2	1.5
Bamboo fiber	10	1	2.9	2.2	2.2
Bamboo fiber	15	0.5	2.1	1.4	2.8
Bamboo fiber	15	0.75	2.0	3.6	0.7
Bamboo fiber	15	1	2.1	2.2	2.1

It is seen that the sample permeability, or water absorption, is not affected with increasing curing days; however, in many cases it is seen that increasing the percentage of cement content in the sample reduces the water absorption capabilities. This can be seen in both coconut fiber and bamboo fiber-reinforced earth blocks. Moreover, it can be observed that the increasing fiber percentage from 0.5-1% had a nil effect on the water absorption capability. Both coconut fiber and bamboo fiber reinforced earth blocks had similar water absorption properties. All the fiber-reinforced earth blocks had a water absorption percentage of less than 5 percent, which met the minimum requirements of the water absorption capabilities for their use in building construction [42]. A similar study was conducted by Mostafa & Uddin [4] using 0.35% banana fibers to manufacture banana fiber-reinforced earth blocks. It was reported that the average water absorption was 10.6 percent, which is higher compared to coconut fiber and bamboo fiber earth blocks manufactured in this study. In another study by B.O. Ugwuishiwu et al. [42], it was seen that the average water absorption at 1% kernel fiber content was around 5.65 percent. For the compressed earth blocks, an increase in the water absorption capacity was reported. Two factors that influence the water absorption capacity after the coir fiber reinforcement are the fiber's length and content. Raavi and Tripura [43] reported the water absorption varied from 19.37% to 25.87% for samples reinforced with fibers of 25 mm length and increased from 21.06% to 27.18% for samples reinforced with fibers of 50 mm length. The coir fiber ranged from 1 to 5% in their study. It was also reported that the coir fiber percentages above 1% had a negative effect [9, 43, 44], and in the current study the maximum coir fiber percent used is 1%.

Samples underwent a wet compressive strength test following ASTM C1314 to understand the impact of fiber and binder on block porosity and compressive strength after submersion. Results in Table 4 and Figures 11 to 13 revealed that wet compressive strength was generally lower than dry strength for all samples, as water saturates soil particles and weakens bonds. Increased absorption rate not only causes degradation more quickly, but it also drastically weakens the material. Higher water absorption in wet compressive strength of earth blocks is attributed to water saturating the material, filling pores, and reducing load-bearing capacity. Water weakens particle bonds, which is particularly crucial in earth materials reliant on cohesion for structural integrity. Wet conditions cause expansion, creating internal stresses and diminishing compressive strength. Consideration of these moisture-induced changes is essential in construction projects for long-term durability and stability of structures. Increasing cement content in earth blocks, added primarily as a stabilizer, strengthens particle cohesion, reducing water absorption. Higher cement content helps fill voids, contributing to block strength and durability by preventing damage from moisture-related issues.

In Table 4, the characteristics of behavior in terms of the curing days and cement content are the same as those of dry compressive behavior given in Table 2. A 35-39% reduction in compressive strength is seen in the samples containing 15% cement content when compared to dry compressive strength. The optimal composition for earth blocks with coconut fiber reinforcement is 1% fiber with 15% cement, showing impressive dry compressive strength of 2.64 MPa after a 28-day cure. This composition exhibits a 47% strength reduction in wet compressive strength of 1.4 MPa. This combination met the minimum compressive strength of 1.4 MPa as per the NZS4298 [45]. For bamboo fiber, the most effective composition is 1% fiber with 15% cement, achieving a dry compressive strength of 3.24 MPa after 28 days with a 40% reduction in compressive strength in wet tests at 1.96 MPa. Lower fiber percentages still provide ample reinforcement, and the 15% cement content enhances binding and reduces water absorption, resulting in minimal strength loss. Overall, 1% bamboo fiber with 15 cement stands out as an ideal choice for creating reliable and sustainable earth blocks in the construction industry. The addition of fibers to earth blocks enhances strength, mainly due to cement acting as a binder, forming a robust bond. In this study, the best composition achieved a maximum strength of 3.24 MPa, falling below the recommended range (4.3–6.9 MPa) for direct construction use [21]. However, it holds potential for reinforcing soil structures around foundations, embankments, and retaining walls, where lower strength demands are acceptable as per the certain standards [45-47].

Table 4. Wet compressive strength of samples without any fiber reinforcement

Composition	Average Strength (*MPa*) 7 days curing	Average Strength (*MPa*) 14 days curing	Average Strength (*MPa*) 28 days curing
Clay soil earth blocks	0	0.01	0.02
Clay soil with 5% cement earth blocks	0.09	0.13	0.16
Clay soil with 10% cement earth blocks	0.21	0.31	0.37
Clay soil with 15% cement earth blocks	0.51	0.73	1.03

Material and Construction for Earth Blocks NZS4298 [45] was used as reference material. The code specifies that the compression strength to be more than 1.4 MPa. The comparative analysis of various earth blocks against the NZS4298 standard strength of 1.4 MPa shows that the composition with 1% bamboo fiber with 15% cement and 1% coconut fiber with 15% cement consistently exceed the standard at all curing periods (7, 14 and 28 days), with 1% bamboo fiber with 15% cement demonstrating the highest overall strength. Composition without fiber with 15% cement, while initially below the standard at 7 and 14 days, meets the standard by 28 days. The 0.5% coconut fiber with 15% cement composition slightly exceeds the standard at 28 days and 0.75% bamboo fiber with 15% cement surpasses the standard at all curing days. Overall, 1% bamboo fiber with 15% cement and 1% coconut fiber with 15% cement are the most reliable compositions for achieving and exceeding the required strength parameters in line with NZS4298 across various curing periods. Moreover, 1% bamboo fiber with 15% cement has met the minimum compressive strength for all the standards specified in Table 5.

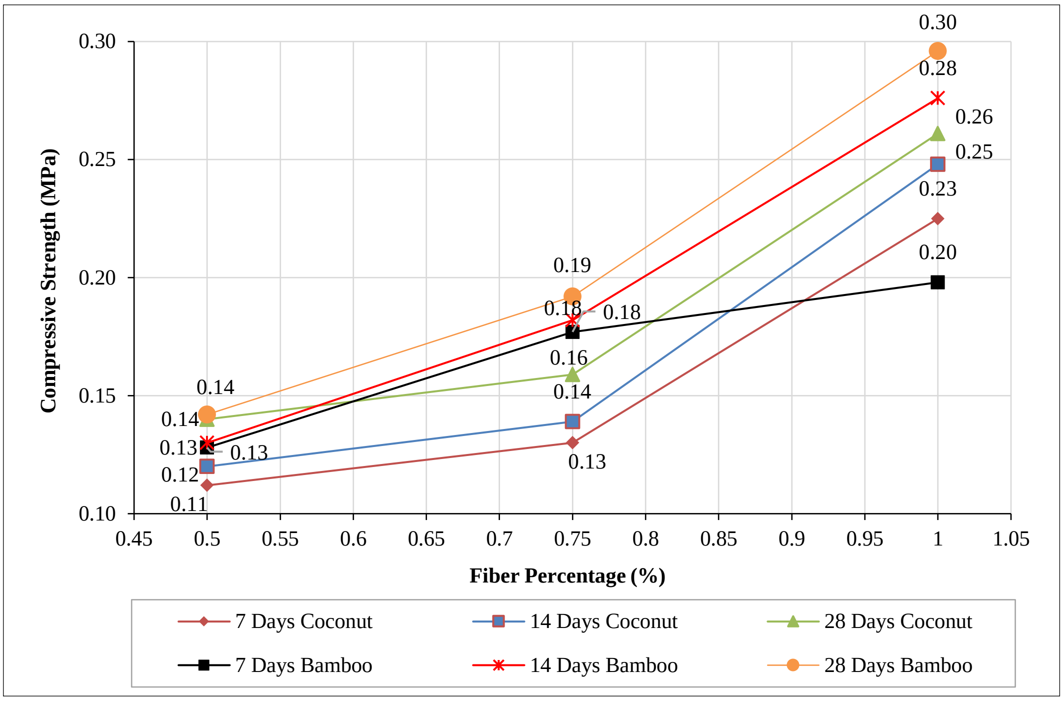

Figure 11. Wet compressive strength of fiber reinforced earth block with 5% cement

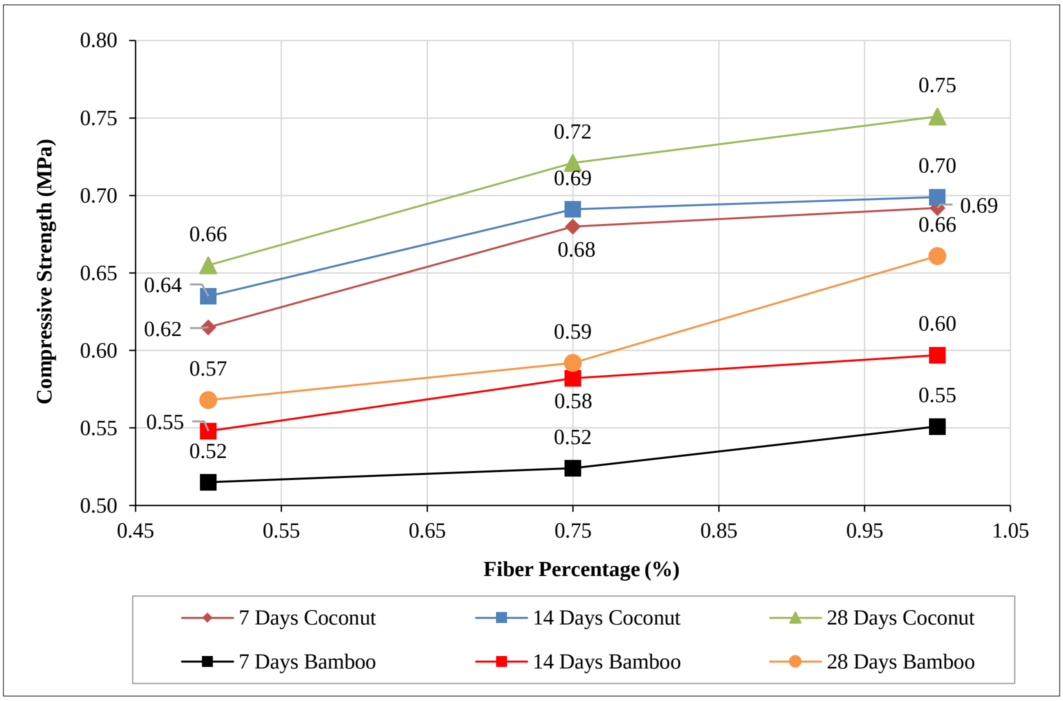

Figure 12. Wet compressive strength of fiber reinforced earth block with 10% cement

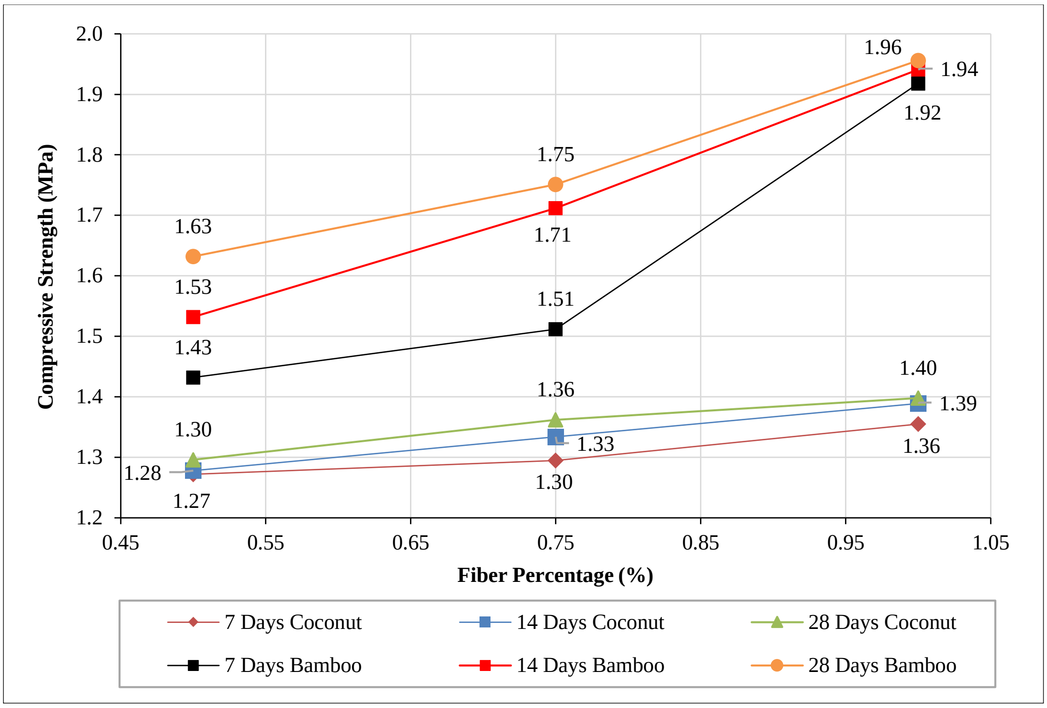

Figure 13. Wet compressive strength of fiber reinforced earth block with 15% cement

Table 5. Wet compressive strength of samples without any fiber reinforcement

Composition	Average Strength (*MPa*) 7 days curing	Average Strength (*MPa*) 14 days curing	Average Strength (*MPa*) 28 days curing	NZS4298 Standard	Other Standards
1% bamboo fiber with 15% cement	2.13	2.49	3.24	1.4 MPa	0.7 MPa (Standards Australia) [46], 1.4 MPa (Indian Standard) [47], 2.8 MPa (Sri Lankan Standard, Grade 3) [10], 3 MPa (German Standard, grade 3) [10], 2 MPa (Brazilian Standard) [10].
1% coconut fiber with 15% cement	1.63	1.84	2.64		
Clay soil with 15% cement	0.83	1.16	1.58		
0.5% bamboo fiber with 15% cement	1.63	1.70	1.72		
0.75% bamboo fiber with 15% cement	1.87	2.10	2.46		

The compressive strength of earth blocks with natural fibers compared to standard concrete blocks can vary significantly depending on several factors, including the type of soil, the type and the number of natural fibers used, the curing process, and environmental conditions. The compressive strength of earth blocks with natural fibers typically ranges from 2 to 10 MPa [19, 24]. The inclusion of natural fibers, such as straw, bamboo, coconut coir, or sisal, can help improve tensile strength and reduce shrinkage cracks, but they often do not significantly increase compressive strength. Standard concrete blocks generally have a higher compressive strength, ranging from 15 to 35 MPa [48, 49], depending on the mix design, curing, and the specific type of concrete block. Concrete blocks are made with cement, aggregates, and water, which provide a uniform and high compressive strength once fully cured. In wet conditions, earth blocks can lose a significant amount of their strength because water can dissolve or weaken the clay particles that bind the soil together. The presence of natural fibers can help maintain some structural integrity by providing reinforcement, but the blocks are generally more susceptible to moisture compared to concrete. Concrete blocks are less affected by moisture because the cement matrix is not soluble in water once it has fully cured. The wet compressive strength of concrete blocks is generally lower compared to their dry strength, typically decreasing by 15-25% depending on the water absorption characteristics of the aggregates used [49].

Furthermore, Sujatha et al. [44] demonstrated that earthen blocks reinforced with natural fibers proved to be the most cost-effective option among the fibers studied. Natural fiber-reinforced earth block is economical, sustainable, and environmentally friendly because it uses locally available soil fibers and uses little water and energy [17]. Compressed earth blocks can reduce costs by 8.65% when used in place of burned clay bricks, as shown by Paul et al. [50]. Using identically sized blocks of both types, they examined the construction costs of a full-floor building of 6.9 m × 5.8 m × 3.05 m. The cost of the burned clay bricks option was USD 1303, whereas the compressed earth blocks option was USD 1208. Furthermore, they emphasized that, in the six environmental areas they looked at for their study, compressed earth blocks have a lesser environmental impact. Moreover, the cost savings of 7.25% are achieved by using the compressed earth blocks solution, which is 92.25% less expensive than the sand-cement brick option. According to the findings of Bailly et al. [24], Masuka et al. [34], and Sujatha et al. [44], durability and compressive strength increased with an increase in cement content; however, the cost also increased. The necessity of striking a balance between mechanical performance and financial concerns is highlighted by their observation that a higher cement percentage could lead to higher material costs.

When compared to earth blocks, the development and use of concrete blocks may have various negative effects on the environment. First, earth blocks are generally manufactured from soil that is obtained locally, necessitating little processing. Concrete blocks, on the other hand, are created by combining cement, water, sand, and gravel. Significant amounts of CO_2 are released during the highly energy-intensive process of making cement [1]. Second, compared to concrete blocks, earth blocks usually take less energy to make, particularly if they are stabilized with small amounts of lime or cement. Can be produced locally using low-energy or manual machinery, which eliminates the need for transportation and the related emissions [2]. Conversely, the high temperatures needed to make cement mean that producing concrete blocks requires a lot of energy. The energy consumption for transporting raw materials and finished products can be significant, especially if materials are sourced from far away [1]. Some of the practical challenges in implementing these earth blocks in construction projects are the availability and suitability of soil and consistency in production. Locating suitable soil can be challenging and time-consuming. Further, obtaining uniform strength and quality may be difficult with varying soil properties. Additionally, setting precise specifications and rules for the manufacture and building of earth blocks can assist in ensuring quality and fostering consumer confidence in the product. Many places have building laws and regulations that are oriented toward standard materials like steel and concrete. Approval of earth blocks can be a drawn-out, bureaucratic process. If you compare earth blocks to more conventional materials like burnt bricks or concrete, you might think they're not as strong or long-lasting. It will take education and proof of the advantages of the blocks to change this belief. Building quality and market acceptance can be raised by educating engineers, architects, and builders on the advantages and appropriate application of earth blocks [51].

5. Conclusion

In this study, the compressive strength and water absorption properties were evaluated on the coconut fiber and bamboo fiber-reinforced clay soil earth blocks. The results presented important insight on fiber and cement percentages on the performance of the clay soil earth blocks. In summary, the fibers from bamboo and coconut show promising results for applications in strengthening soil beneath foundations and pavements, reducing settlement issues, and enhancing stability in fragile soil. Unreinforced clay soil without the addition of cement stabilizer showed maximum compressive strength of 0.07 MPa. Stabilized unreinforced clay soil's compressive strength further improved with the addition of 15% cement stabilizer to 1.58 MPa. With the addition of coconut fibers, a significant increase in compressive strength is obtained with a value of 2.64 MPa, an increase of 67% in strength. With the addition of bamboo fibers, a significant increase in compressive strength is obtained with a value of 3.24 MPa, an increase of 105% in strength. Wet compressive strength was significantly lower when compared to dry compressive strength, with the maximum strength of 1.96 MPa for 1% bamboo fiber containing 15% cement stabilizer cured for 28 days. Because of the resistance provided by fibers during compaction, there is an irregular relationship between the water absorption of blocks and fiber content at the same compaction energy and cement content. The authors advise using 10-15% cement for stabilization and strength enhancement of rammed earth blocks and an ideal quantity of 1% coconut fiber and 0.75-1% bamboo fiber for reinforcement. The strength of raw soil blocks is greatly impacted by using coconut fiber and bamboo fiber as reinforcement in rammed earth blocks.

6. Declarations

6.1. Author Contributions

Conceptualization, T.K. and S.N.; methodology, T.K.; validation, R.R.M., S.N., T.K., and R.K.; formal analysis, R.R.M. and R.K.; investigation, R.R.M. and R.K.; writing—original draft preparation, Md.S., K.M., R.R.M., T.K., and R.K.; writing—review and editing, S.N., Md.S., and K.M.; visualization, T.K., Md.S., K.M., and S.N.; supervision, T.K.; project administration, T.K. and S.N. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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