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Application of Bamboo as the Reinforcement for Walls Made Using 3D Printed Clay-Hemp Mixture

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Abstract

This study explores the innovative application of bamboo as reinforcement in walls constructed using a 3D printed clay-hemp mixture. This experimental study investigates the feasibility and effectiveness of using bamboo as reinforcement for walls constructed from a 3D printed clay-hemp mixture. Through a comprehensive literature review, the tensile strength and various reinforcement methods of bamboo are explored, including epoxying onto plastic pipes, taping, and inserting steel rods with hose clamping. The experimental setup involves creating 3D printed clay-hemp specimens reinforced with bamboo and conducting pull-out tests to evaluate the bond strength and overall structural integrity. Three reinforcement techniques are systematically compared to identify the most effective method which are two, one, and no hose clamp attached to the embedded bamboo. Each method's impact on the mechanical properties of the composite material is carefully analyzed. The results indicate that the method involving the extended steel rod with hose clamping is the most effective, yielding a tensile strength of 9504 psi (66 MPa). In addition to experimental findings, the study discusses the broader implications of using bamboo as a reinforcement material in sustainable construction. Bamboo's natural strength, rapid growth, and renewability make it an ideal candidate for eco-friendly building practices. By combining bamboo with 3D printed clay-hemp mixtures, the research demonstrates a viable approach to developing durable and sustainable construction materials. This study contributes to the growing field of eco-friendly building technologies, presenting bamboo-reinforced clay-hemp walls as a promising solution for future construction projects.

Keywords

Bamboo Reinforcement, Cobcrete Structures, Pull-Out Test, Sustainable and Green Infrastructure, Automation in Construction

1. Introduction

The construction industry is increasingly embracing sustainable and eco-friendly materials and techniques to address the pressing challenges of environmental degradation and resource depletion [1] [2]. In this context, the integration of natural fibers like bamboo and hemp with innovative construction methods such as 3D printing holds significant promise for advancing sustainable construction practices. This paper presents an experimental investigation aimed at using bamboo as a reinforcement along with hempcrete for the development of 3D printable cobcrete structures. Three main building materials are used in this study, which are cobcrete, hempcrete, and bamboo. Cobcrete is a building material made from a mixture of clay, sand, straw, lime, and water [3] [4]. Hempcrete is a bio-composite material made from hemp hurds (the woody core of the hemp plant) mixed with a lime-based binder (lime and sand) [5] [6]. Bamboo, recognized as the fastest-growing plant globally, is an eco-friendly and sustainable building material suitable for various decorative and structural applications [7]. The utilization of bamboo in construction dates back centuries, owing to its remarkable strength-to-weight ratio, renewability, and versatility [8]. However, challenges related to its tensile strength and durability have prompted researchers to explore various reinforcement techniques. Concurrently, hempcrete, a bio-composite material comprising hemp fibers and lime-based binders, has gained attention for its excellent thermal insulation properties, low carbon footprint, and biodegradability. By combining these two materials, this research seeks to enhance the mechanical properties and structural integrity of 3D printable cobcrete structures while maintaining their sustainability credentials.

The literature review section provides insights into the tensile strength of bamboo and various methods of enhancing its reinforcement effectiveness to improve its mechanical properties. Techniques such as epoxying on a plastic pipe, taping, and inserting steel rods with hose clamping are explored to ascertain their effectiveness in enhancing bamboo's tensile strength. Additionally, the section delves into the properties and advantages of hempcrete, laying the foundation for its integration with bamboo in the experimental investigation.

The primary focus of this study lies in conducting pull-out tests to evaluate the bond between bamboo and hempcrete in the context of 3D printable cobcrete structures. A series of experiments are conducted, including the 3D printing of cobcrete specimens and the evaluation of different reinforcement methods. These methods include the use of extended steel rods with hose clamps both inserted and removed, as well as configurations without extended steel rods and hose clamps.

The experimental setup and results of the analysis provide valuable insights into the effectiveness of each reinforcement enhancement technique in improving the bond between bamboo and hempcrete, thereby contributing to the development of robust and sustainable construction materials and methodologies.

Overall, this experimental investigation represents a significant step towards harnessing the potential of natural fibers and bio-composite materials in the realm of 3D printable construction. By reinforcing bamboo with hempcrete, this research endeavors to overcome existing challenges and pave the way for the widespread adoption of eco-friendly and resilient building materials, thereby advancing sustainable construction practices for the benefit of both present and future generations.

2. Literature Review

Bamboo has garnered significant attention as a sustainable building material due to its remarkable properties, including high strength-to-weight ratio, renewability, and rapid growth cycle. It is a versatile material that has been traditionally used in various construction applications, ranging from scaffolding and structural frameworks to flooring and wall panels [9]. Bamboo's tensile strength is particularly noteworthy, making it an ideal candidate for reinforcement in construction elements subjected to bending and tension loads.

Bamboo stands out as a sustainable construction material for various reasons, supported by quantitative data that underscores its environmental benefits and structural capabilities. Firstly, bamboo's remarkable growth rate makes it highly renewable, with some species capable of growing up to 91 cm (36 inches) in a single day. This rapid growth allows for quick replenishment of harvested resources, minimizing environmental impact. In contrast, traditional hardwood trees used in construction can take decades to mature. Moreover, bamboo's strength-to-weight ratio surpasses that of steel, with tensile strength comparable to mild steel and compressive strength superior to concrete. Quantitatively, bamboo's tensile strength can range from 8700 psi (60 MPa) to 28,000 psi (193 MPa), while its compressive strength varies between 5800 psi (40 MPa) to 8700 psi (60 MPa) [10], both for loading applied parallel to grain, noting that the sample length is short enough to avoid buckling under compression [11]. **Figure 1** shows the bamboo's compressive test setup. These figures demonstrate bamboo's structural integrity, making it suitable for a wide array of construction applications, from scaffolding to flooring and even load-bearing elements in buildings. In terms of carbon sequestration, bamboo outperforms many other building materials. It absorbs carbon dioxide at a faster rate than hardwood trees, with estimates suggesting that bamboo can sequester up to 12 tons of CO_2 per hectare annually [12] [13]. This carbon sequestration potential contributes to mitigating climate change and reducing the carbon footprint associated with construction projects.

Furthermore, bamboo's versatility extends to its water efficiency. It requires significantly less water to grow compared to traditional timber species, with some estimates suggesting that bamboo consumes only a fraction of the water needed for equivalent hardwood production [13]. This aspect is particularly crucial in regions facing water scarcity or where sustainable resource management is prioritized. Additionally, bamboo's natural resistance to pests and diseases reduces the need for chemical treatments, further enhancing its eco-friendly attributes. Quantitative data on pesticide and fungicide use in bamboo cultivation compared to conventional timber production illustrates this advantage, showcasing bamboo as a low-impact and environmentally sound choice for construction materials [14].

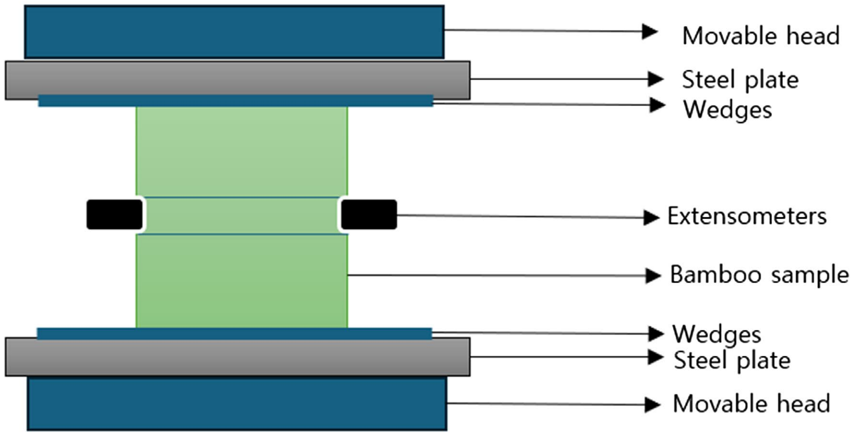

Figure 1. Compressive test setup.

Several methods have been employed to enhance the mechanical properties of bamboo for structural applications. Epoxying bamboo onto a plastic pipe is a common technique used to increase its bending and tensile strength [15]. This method involves saturating bamboo fibers with epoxy resin and then wrapping them around a plastic pipe to form a composite structure. Moreover, inserting extended steel rods into bamboo poles and clamping them with hoses further enhances the structural performance of bamboo elements [16] [17]. These reinforcement techniques offer flexibility and customization in strengthening bamboo for various construction purposes.

According to a study made by [17], in order to improve the bond stress between the bamboo reinforcing bars and the surrounding concrete, pull-out tests were conducted on variously bonded specimens. The bonding methods are via brush coating or spraying synthetic resin and synthetic rubber, with a pull-out test setup. The bond strength covering with full treatment shows the high value 1.2 - 1.35 MPa [18] [19]. The results indicated that surface treatment significantly influenced bond stress, with fully treated specimens exhibiting higher bond stress compared to partially treated or untreated specimens. Additionally, the bond-slip behavior showed that bamboo exhibited higher bond strength compared to plain steel bars, with friction forces contributing to consistent bond stress after maximum bond strength was reached. The tensile strength of bamboo can also be tested in various methods of gripping such as wire spiral at the end, rectangular flat end, and grooving [19].

Hempcrete, a composite material made from hemp fibers and lime-based binders, has gained recognition as a sustainable alternative to conventional construction materials [20]. It exhibits excellent thermal insulation properties, fire resistance, and moisture regulation capabilities [21]. Hempcrete is lightweight, breathable, and non-toxic, making it suitable for a wide range of construction applications, including insulation, wall panels, and structural elements [22] [23]. The use of hempcrete contributes to carbon sequestration, as hemp plants absorb carbon dioxide during growth, making it a carbon-negative building material [23]. Moreover, hempcrete has low embodied energy and can be produced using locally sourced materials, further enhancing its sustainability credentials.

The combination of bamboo reinforcement with hempcrete presents a compelling solution for sustainable construction practices. By integrating these renewable materials, it is possible to develop lightweight, durable, and eco-friendly building elements with enhanced structural performance. The synergy between bamboo's tensile strength and hempcrete's thermal insulation properties offers opportunities for innovative construction designs and applications. Previous studies have demonstrated the feasibility of using bamboo-reinforced hempcrete in various construction projects, highlighting its potential for reducing environmental impact and promoting sustainability in the built environment. However, further research is needed to explore the optimal integration techniques, material compositions, and structural design considerations to maximize the benefits of this composite material system. **Figure 2** shows a bamboo reinforced rammed earthen wall [24].

Figure 2. Bamboo reinforced rammed earth wall (figure copied from [24]).

Using bamboo in 3D printing for earthen residential houses is considered green and low-carbon due to several key factors:

a) Sustainability and Renewability: Bamboo grows much faster than traditional timber, reaching maturity in 3 - 5 years compared to 20 - 50 years for most hardwoods. It can also produce a higher biomass per hectare compared to trees, making it a highly efficient resource. Moreover, bamboo cultivation requires less land, helping preserve ecosystems and reduce deforestation.

b) Carbon Sequestration: Bamboo absorbs more CO_2 and releases 35% more oxygen into the atmosphere compared to an equivalent mass of trees. When used in construction, the carbon captured by bamboo remains sequestered for the lifespan of the building.

c) Low Energy Consumption: Bamboo does not require significant energy for processing and can often be used in its natural form, reducing the carbon footprint associated with manufacturing. In many regions, bamboo is locally available, reducing transportation energy and emissions.

d) Reduced Construction Waste: 3D printing with bamboo allows for precise application, minimizing material waste. The process can be fine-tuned to use only the necessary amount of material.

e) Biodegradability: Bamboo is biodegradable, reducing the environmental impact at the end of the building's life cycle compared to non-biodegradable materials like concrete and plastics.

f) Enhanced Insulation Properties: Bamboo has excellent thermal insulation properties, reducing the need for energy consumption in heating and cooling homes.

In summary, the literature review highlights the significant potential of bamboo-reinforced hempcrete for 3D printable cobcrete structures. By leveraging the unique properties of bamboo and hempcrete, it is possible to develop sustainable construction solutions that address the challenges of environmental sustainability and climate change mitigation. The subsequent sections of this study will delve into experimental investigations to assess the feasibility and structural performance of bamboo-reinforced hempcrete for 3D printable cobcrete structures, contributing to the advancement of eco-friendly construction methodologies.

3. Methodology

Bamboo, recognized for its remarkable mechanical properties and rapid growth, has emerged as a sustainable alternative to traditional construction materials. Its tensile strength is particularly significant, as it directly influences its effectiveness as a reinforcement material in various structural applications. This section aims to explore different methods of enhancing bamboo's gripping capabilities during tensile strength testing, as outlined in the literature review. By employing innovative reinforcement techniques, the study seeks to optimize bamboo's performance under tensile loads, thereby increasing its potential for widespread use in eco-friendly construction practices.

To assess the impact of these reinforcement methods, a series of experimental setups were conducted using a universal testing machine. The focus was on implementing four distinct techniques designed to improve the gripping of bamboo specimens during tensile testing. These methods include epoxying bamboo to a plastic pipe, applying high-strength tape to the bamboo tips, inserting a steel rod for internal reinforcement, and utilizing an extended steel rod with hose clamping. Each method's effectiveness will be analyzed based on the tensile strength results obtained from the tests. The subsequent sections provide a detailed examination of each reinforcement technique, along with their respective setups, results, and implications for enhancing the mechanical performance of bamboo in construction.

3.1. Methods of Reinforcement Enhancement through Improved Gripping

As discussed in the literature review, bamboo can be enhanced as a reinforcement through several methods to improve its gripping for the tensile strength test. The techniques used in this study for such enhancement of reinforcing function of bamboo are discussed:

Epoxying on a Plastic Pipe: In this method, a plastic pipe was prepared by cleaning its surface to remove contaminants. An epoxy resin adhesive was applied uniformly to the exterior surface of the pipe, ensuring full coverage. Both ends of the bamboo culm were then firmly attached to the epoxy-coated pipe, and the assembly was left to cure at room temperature for 24 hours. The epoxy resin formed a strong bond between the bamboo and the pipe, providing enhanced gripping strength. The dimensions of the plastic pipe were chosen to match the bamboo's outer diameter, ensuring a snug fit as shown in Figure 3.

Figure 3. Epoxying bamboo on a plastic pipe.

Taping: For this method, industrial-grade high-strength adhesive tape was used to wrap around the ends of the bamboo culm. The tape was applied in multiple layers with an overlap of at least 50% to maximize gripping strength and prevent slippage. The total length of the taped section was standardized to 50 mm on each end of the bamboo specimen as presented in Figure 4. This method helped to confine the bamboo fibers, reduce splitting, and improve the load transfer between the bamboo and the testing apparatus.

Figure 4. Taping bamboo tips.

Inserting Steel Rod and Hose Clamping: A steel rod of 6 mm diameter was inserted into the hollow center of the bamboo culm, extending approximately 50 mm into each end. Hose clamps were then placed around the bamboo tips to tightly secure the steel rod within the culm as shown in Figure 5. The clamps were tightened uniformly using a torque wrench set to 10 Nm to ensure consistent clamping force across all specimens. This configuration provided internal reinforcement and distributed stress evenly along the bamboo's length during tensile testing.

Figure 5. Inserting steel rod and hose clamping bamboo tips.

Inserting Extended Steel Rod and Hose Clamping: This technique built upon the previous method but involved using a steel rod that extended beyond the length of the bamboo culm. The rod was inserted 50 mm into the bamboo and protruded an additional 100 mm from the culm's end to allow direct gripping by the tensile testing machine. Hose clamps, identical to those in the previous method, were used to secure the rod in place as shown in Figure 6. The extended steel rod minimized stress concentration at the bamboo ends and ensured consistent load application during testing.

Figure 6. Inserting extended steel rod and hose clamping bamboo tips.

3.2. Test Setup and Results

The tensile strength of bamboo was tested using a universal testing machine, as depicted in **Figure 7**. The bamboo test specimens had a diameter of 11 mm (0.43 in) and belonged to the species *Schizostachyum zollingeri*, commonly found in tropical and subtropical climates [25] [26]. According to literature reviews, the tensile strength of this bamboo species is reported to be 9862 psi (68 MPa) [26]. To prevent splitting and slipping of the bamboo during testing, four different reinforcing methods were implemented for gripping. The tensile test results for all methods are summarized in **Table 1**. It was observed that the extended steel rod with hose clamping method yielded the highest tensile strength of 9504 psi (66 MPa), with only a 3.6% discrepancy from the literature value, and an applied force of 1400 lbs. The failure mode observed in this method was fracture. Conversely, gripping the bamboo tip without an extended steel rod and hose clamp resulted in the lowest tensile strength of 1697 psi (12 MPa), as the bamboo slipped out at a load of 250 lbs.

Figure 7. Testing bamboo's tensile strength in a universal testing machine.

Table 1. Tensile strength test results for four different gripping.

Gripping type	Epoxying	Taping	Steel rod with hose clamp	Extended steel rod with hose clamp
Load (lbs)	1200	750	250	1400
Tensile Strength (psi/MPa)	8147 (56)	5092 (35)	1697 (12)	9504 (66)

4. Pull-Out Test

4.1. 3D Printing Cobcrete Specimens and Filling Hempcrete

The process of 3D printing cobcrete specimens that serve as small sample sections of walls for reinforcing bamboo with embedded hempcrete within their void cells, entails selecting a buildable mixture, designing appropriate toolpaths that mimic the 3D printable cobcrete enclosure of a house, and optimizing printing parameters. In this study, the most workable, flowable, and buildable cobcrete mixture, comprising clay, lime, sand, hemp fiber, and water, as detailed in **Table 2** from the authors' previous study, is utilized [27]. The toolpath design adopted for this experiment features a section of a honeycomb pattern rectangular wall. This pattern is selected due to the fact that honeycomb infill patterns typically offer higher moment of inertia compared to rectilinear infill patterns. The honeycomb pattern's efficiency in material distribution results in a greater concentration of material located farther from the axis of rotation, thereby enhancing resistance to bending and torsional forces, and ultimately improving overall strength and stability [28] [29]. **Figure 8** illustrates the toolpath design of four interconnected sections of cobcrete wall pieces, facilitating a faster printing process compared to designing individual wall sections for printing. The 3D printing parameters setting employed in this experiment, including robot speed, nozzle diameter, layer width, layer height, etc., are outlined in **Table 3**. Once the four connected pieces are printed, they are separated from each other, as depicted in **Figure 9**. Subsequently, a hempcrete mixture specified in **Table 4** is filled into the void cells of the 3D printed cobcrete specimens to embed the bamboo reinforcements for the pull-out test while the cobcrete print is in its fresh state as shown in **Figure 10**.

Table 2. Mixture of cobcrete.

Raw Material	%
Clay	17.5
Sand	40
Lime	18
Water	22.5
Hemp	2
Additive	0
Total	100

Table 3. 3D printing parameters.

Printing Parameter	Value
Nozzle speed	20% of 150 mm/sec
Pump extrusion rate	0.9 l/min
Nozzle diameter	25 mm
Bead width	30 mm
Layer height	15 mm
Toolpath Property	**Value**
No. of layers	10
No. of beads	6
Height of specimen	150 mm
Width of specimen	160 mm
Length of specimen	160 mm

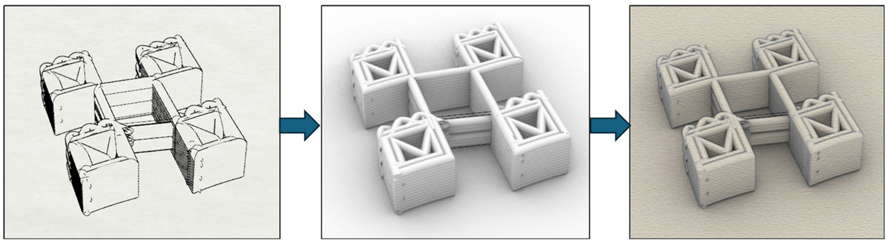

Figure 8. Toolpath design of the cobcrete specimens.

Figure 9. 3D printed cobcrete specimens.

Table 4. Mixture of hempcrete.

Raw Material	%
Lime	48
Water	46
Hemp	6
Total	100

Figure 10. 3D printed cobcrete specimen with embedded hempcrete fillers in the void cells.

4.2. Bamboo-Hempcrete Bond

In the pull-out test, the bond between bamboo and hempcrete is pivotal, alongside the cobcrete-hempcrete bond [29]. To assess the impact of connections on bond stress, three distinct methods are employed. The first specimen features two hose clamps attached to the embedded bamboo, while the second and third specimens have one and no hose clamps attached, respectively. Additionally, the surface of the bamboo is uniformly roughened using sandpaper along its entire embedded length. Consistent with Section 3, the same species and size of bamboo are utilized—an 11 mm (0.43 in) diameter *Schizostachyum zollingeri*—with an embedded length equivalent to five times the diameter, totaling 55 mm (2.17 in) [30]. The gripping reinforcement chosen is the extended steel rod with hose clamping, ensuring consistency in achieving the previously attained tensile strength of 9504 psi (66 MPa). Illustrated in **Figure 11** is the 3D printed cobcrete with bamboo reinforcement embedded in hempcrete.

Figure 11. Bamboo installation and drying technique.

4.3. Test setup and Results

The pull-out test of the cobcrete samples with bamboo reinforcement embedded in hempcrete fillers is conducted using a universal testing machine. At the top part of the machine, a gripping mechanism is attached to grasp the extended steel rod affixed to the bamboo, while the cobcrete section is secured by a steel clamping device positioned at the corner space of the cobcrete without interfering with the void cells. The test setup is depicted in Figure 12. Three distinct bamboo-hempcrete bonding methods, as discussed in Section 4.2, are employed, resulting in three test specimens for each method. Experiment results are detailed in Table 5, and Figure 13 illustrates the setup along with the pulled-out pieces for each bonding method. The findings indicate that the highest bond strength is achieved with the specimen featuring two hose clamps attached, measuring 1215 psi (8 MPa), while the lowest strength is recorded for the specimen with no hose attached, measuring 176 psi (1.2 MPa)—a notable 590% drop in strength. This discrepancy underscores the significant influence of bonding methods on bond strength.

In general, the experimental investigation highlights the potential of natural fibers and bio-composite materials in 3D printable construction, focusing on enhancing bamboo's structural performance through innovative reinforcement techniques and integrating it with hempcrete. The results indicate that the method involving the extended steel rod with hose clamping is the most effective, yielding a tensile strength of 9504 psi (66 MPa), close to the literature value for the bamboo species *Schizostachyum zollingeri*. This method minimized slippage and splitting, demonstrating its potential for maximizing bamboo's tensile strength in construction applications. This research demonstrates that by addressing the challenges associated with bamboo reinforcement, such as improving tensile strength and bond performance, bamboo can be a viable, eco-friendly material for 3D printable construction. The integration of hempcrete further enhances its sustainability and resilience, offering promising prospects for advancing sustainable construction practices.

Figure 12. Pull-out test setup.

Table 5. Pull-out test result for three different embodiments.

Embedment Type	Specimen	Load (lbs)	Bond Strength (psi/MPa)
2 Hose Clamps	Specimen 1	182	1235 (8.5)
	Specimen 2	179	1215 (8.4)
	Specimen 3	176	1195 (8.2)
	Average	179	1215 (8.4)
	Std. Dev.	3.1	16.4 (0.11)
1 Hose Clamp	Specimen 1	124	842 (5.8)
	Specimen 2	122	828 (5.7)
	Specimen 3	120	814 (5.6)
	Average	122	828 (5.7)
	Std. Dev.	2.0	14.0 (0.10)
No Hose Clamp	Specimen 1	28	189 (1.3)
	Specimen 2	26	176 (1.2)
	Specimen 3	24	163 (1.1)
	Average	26	176 (1.2)
	Std. Dev.	2.0	13.0 (0.09)

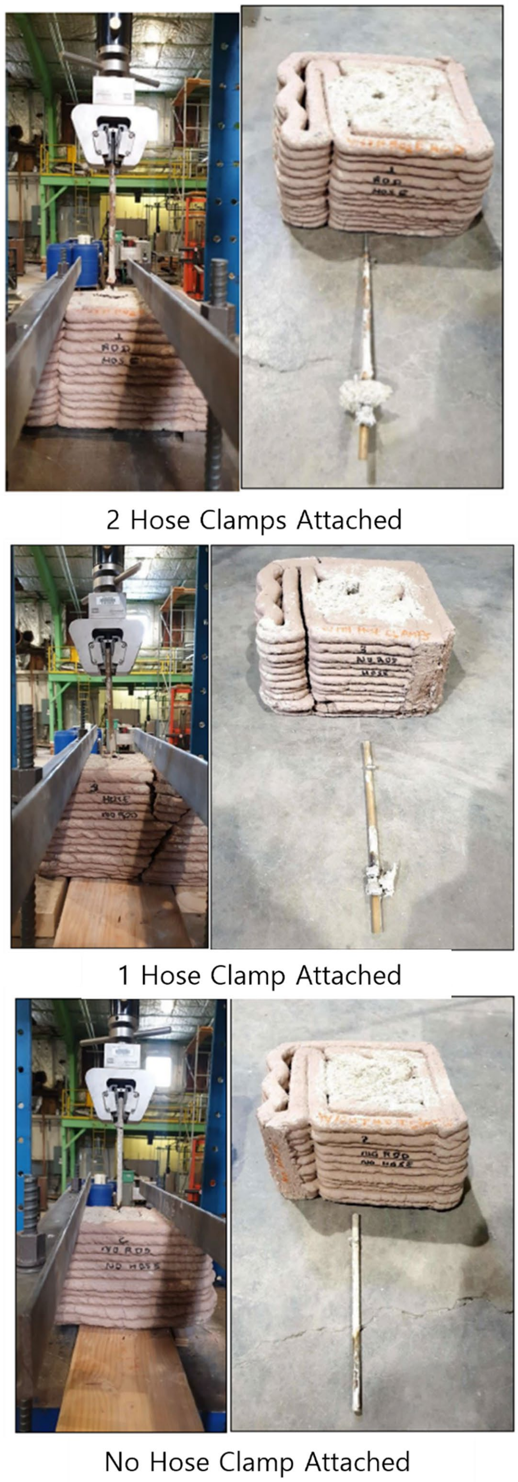

Figure 13. Test setup and pulled out pieces for each bonding method.

4.4. Discussions and Future Studies

4.4.1. Strength Tests

While the results presented in this paper provide valuable insights into the material properties of the clay-hemp composite mixture, particularly through the pull-out tests, we acknowledge the limitation that these experiments were conducted solely in a controlled laboratory environment. Although these tests offer crucial data on the fundamental behavior of the material, it is essential to note that broader-scale tests are needed to fully assess its effectiveness in real-world construction settings.

Laboratory tests, such as the pull-out tests, serve as an initial indicator of the potential for clay-hemp mixtures in sustainable construction. However, construction projects face a wide range of external factors, such as environmental loads, long-term durability concerns, and construction methodologies that cannot be fully simulated in a laboratory. Without broader-scale studies, such as full-scale structural testing or in-situ performance evaluations, there is a risk of limiting the direct applicability of these findings to practical construction scenarios. These broader tests would provide critical information on how the material behaves under real-world conditions, including how it interacts with other structural elements and its performance under varying environmental stresses.

We plan to expand upon the current research by implementing full-scale construction tests in future studies. These larger-scale experiments would involve the use of clay-hemp mixtures in actual building projects, allowing for the evaluation of structural performance under real-world conditions. Such studies would offer a more comprehensive understanding of the material's capabilities, addressing factors such as load-bearing capacity, long-term weathering, and potential degradation over time.

Despite the current focus on laboratory results, the data generated through pull-out tests lay an important foundation for understanding the material's basic mechanical properties. By supplementing these findings with broader-scale tests, the clay-hemp mixture can be validated for real-world applications, potentially offering a viable and sustainable solution for affordable housing and eco-friendly construction in the near future.

4.4.2. Durability and Environmental Impact Tests

Clay-hemp composites, as well as bamboo-reinforced structures, are susceptible to environmental degradation, especially in humid or variable temperature conditions. Factors such as moisture absorption, freeze-thaw cycles, and microbial activity could significantly affect the long-term structural integrity of these materials. Therefore, long-term durability studies should evaluate resistance to moisture, temperature fluctuations, and biological degradation.

In terms of moisture resistance, bamboo and clay-hemp composites are particularly vulnerable to water absorption, which can lead to swelling, softening, and eventual weakening of the material matrix. For example, untreated natural fibers like hemp can absorb as much as 25% - 30% of their weight in water, depending on environmental conditions [30]. Similarly, bamboo, though strong and lightweight, is prone to fungal attack and rotting in high-humidity environments without adequate protection or treatment.

Similarly, temperature fluctuations, especially freeze-thaw cycles, may cause expansion and contraction in the clay matrix, leading to cracks and loss of mechanical integrity. Natural fiber-reinforced composites subjected to freeze-thaw cycles can lose up to 15% - 20% of their initial strength within a year of exposure. Moreover, microbial impact, such as fungal or bacterial growth, can exacerbate these issues, particularly in the presence of organic materials like hemp and bamboo.

To address these critical durability aspects, future research will focus on:

a) Moisture Resistance: Testing clay-hemp composites under varying humidity levels and introducing protective coatings or water-repellent treatments to reduce moisture absorption.

b) Temperature Variation Testing: Subjecting the materials to freeze-thaw cycles and high-temperature environments to measure the extent of thermal-induced degradation.

c) Microbial Impact Study: Evaluating the material's resistance to mold, fungi, and bacterial degradation under both natural and artificial conditions, possibly integrating biocides or natural preservatives to enhance durability.

4.4.3. Cost Analysis

A detailed cost analysis is necessary to assess whether this approach can be competitive with other building materials, such as steel, concrete, and timber, on a larger scale. Below, we present a preliminary cost comparison based on material prices, labor, transportation, and implementation costs for bamboo-reinforced structures and conventional building materials.

Table 6. Estimated total costs for bamboo-reinforced clay-hemp composite vs. conventional materials (per m^3) [30].

Material	Unit cost (per m^3)	Labor cost	Transportation cost	Total cost
Bamboo-reinforced clay-hemp composite	\$150 - \$200	Moderate	Low	\$300 - \$350
Concrete (with steel reinforcement)	\$120 - \$160	High	High	\$400 - \$500
Timber	\$250 - \$300	Moderate	Moderate	\$400 - \$450

As shown in **Table 6**, the estimated total cost of bamboo-reinforced clay-hemp composites falls between \$300 and \$350 per cubic meter, making it a competitive option, especially when factoring in the lower transportation and energy costs associated with sourcing bamboo locally. While the material costs of concrete are relatively low, labor and transportation expenses drive up the total cost, especially in remote or underdeveloped regions. Bamboo-reinforced material also offers significant potential for lowering long-term costs through reduced energy consumption during production and assembly, particularly in 3D-printed construction.

4.4.4. Additional Reinforcement Techniques

The current study primarily tested conventional reinforcement techniques such as epoxy bonding and hose clamping for bamboo reinforcement in clay-hemp composites. While these methods are widely used, there are also advanced reinforcement methods that can be further investigated in future studies.

Techniques such as fiber-reinforced polymer (FRP) wraps, which provide enhanced tensile strength and durability, or bio-based resins and adhesives that promote better bonding with bamboo, could be explored in future studies. Additionally, integrating graphene-enhanced adhesives or nanomaterial-based coatings could significantly improve the adhesion and durability of bamboo in composite structures, particularly for load-bearing applications.

4.4.5. Life-Cycle Analysis (LCA) and Environmental Impact

An LCA would take into account the carbon footprint of producing, transporting, and implementing these materials, as well as their long-term environmental performance compared to conventional materials like steel, concrete, and timber.

Bamboo-based composites have a significantly lower carbon footprint than conventional construction materials, primarily due to bamboo's rapid growth rate and carbon-sequestering properties. For example, bamboo can absorb approximately 12 tons of CO_2 per hectare annually, making it one of the most sustainable building materials available. When paired with clay-hemp composites, which also have a low carbon footprint due to their natural composition, the overall environmental impact is expected to be far lower than that of traditional materials.

However, a full LCA would consider not just the production phase but also the transportation, assembly, maintenance, and eventual disposal or recycling of these materials. Table 7 provides a preliminary comparison of the estimated carbon emissions for bamboo-reinforced composites and conventional materials.

Table 7. Estimated life-cycle emissions for bamboo-reinforced composites vs. conventional materials (per m^3) [30].

Material	Production emissions (kg CO_2/m^3)	Transportation emissions	End-of-Life emissions	Total Emissions
Bamboo-reinforced clay-hemp composite	20 - 30	Low	Negligible (recyclable)	40 - 50
Concrete (with steel reinforcement)	300 - 400	High	Moderate	500 - 600
Timber	50 - 70	Moderate	Low	100 - 150

The significantly lower emissions for bamboo-reinforced clay-hemp composites highlight their potential as an environmentally sustainable alternative to traditional construction materials. Future work should include a detailed LCA that covers the entire life cycle, from raw material extraction to end-of-life disposal or recycling, to validate the environmental advantages of these composites and further optimize their carbon footprint.

5. Conclusions

The experimental investigation conducted in this study has provided valuable insights into the tensile and pull-out strength characteristics of bamboo-reinforced cobcrete structures embedded with hempcrete fillers. Four reinforcement techniques were evaluated: epoxying bamboo to a plastic pipe, taping bamboo tips, inserting a steel rod with hose clamping, and inserting an extended steel rod with hose clamping. The analysis of tensile strength revealed that the method involving epoxying bamboo onto a plastic pipe yielded the highest tensile strength, with a value of 9504 psi (66 MPa), representing a mere 3.6% deviation from the literature value of 9862 psi (68 MPa) for the bamboo species *Schizostachyum zollingeri*. Additionally, the pull-out test results demonstrated significant variations in bond strength depending on the bonding method employed. Specimens with two hose clamps attached exhibited the highest bond strength at 1215 psi (8.4 MPa), while those with no hose attachment recorded the lowest bond strength at 176 psi (1.2 MPa), indicating 590% drop in strength. These findings underscore the importance of proper bonding techniques in enhancing the structural integrity of bamboo-reinforced cobcrete structures. Furthermore, the successful integration of hempcrete fillers within the cobcrete matrix demonstrates the feasibility of utilizing sustainable materials to reinforce construction elements, thereby contributing to the advancement of eco-friendly building practices. Overall, this research provides a preliminary valuable insight that can inform the design and construction of resilient and sustainable structures using 3D printing of clay-based materials.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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