

Optimizing Natural Binders and Bio-Reinforcements for Enhanced Printability and Mechanical Performance of 3D Printed Soil Structures

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Abstract— 3D printing with soil offers a transformative approach for eco-friendly construction. However, widespread adoption is hindered by the reliance on synthetic binders and reinforcements, leading to detrimental environmental impacts. This study addresses this critical gap by investigating the potential of readily available natural materials for 3D printed soil structures. We explore a novel binder system composed of soil, water, natural gum (e.g., natural gum), and lime, meticulously evaluating its influence on printability (extrusion stability, filament diameter) and interlayer bonding strength (shear bond strength). To further enhance printability and expedite drying times, a commercially available superplasticizer was strategically incorporated at a controlled dosage during the second phase of experimentation. Furthermore, the effect of incorporating bio-reinforcements such as coconut coir and jute fibers (at varying volume fractions) on the mechanical properties (compressive strength, unconfined shear strength) is assessed. The optimized composition, determined through a rigorous series of experiments, is expected to achieve superior printability, bonding strength, and faster drying times compared to unreinforced structures. The strategic selection of bio-fibers, based on their tensile properties and compatibility with the natural binder system, is hypothesized to significantly enhance the mechanical performance of the 3D printed soil. This research paves the way for the development of sustainable 3D printed soil structures, minimizing the environmental impact associated with artificial additives. The findings hold significant promise for advancing eco-friendly construction practices, with potential applications in building affordable and sustainable structures. Notably, the printing process was conducted using a custom extruder mounted on a FANUC R-2000iB/165 robot, demonstrating the scalability of the approach for larger-scale construction projects.

Keywords— Sustainable 3D printing, Eco-friendly construction, Natural binders for 3D printed soil, Bio-reinforcement, UCT

INTRODUCTION

The construction industry faces a pressing need for innovative and sustainable solutions to address the growing demand for efficient and environmentally responsible building practices. 3D printing technology has emerged as a transformative approach, offering significant advantages like reduced waste generation, on-demand fabrication, and enhanced material utilization. Notably, 3D printing with soil presents a particularly attractive avenue for sustainable construction due to the ubiquity and affordability of this natural resource. However, widespread adoption necessitates addressing challenges related to printability and the mechanical performance of soil-based structures.

Conventional 3D printing methods for soil structures often rely on synthetic binders and reinforcements to achieve the desired printability and strength. These synthetic materials raise environmental concerns throughout their lifecycle, from production and use to potential end-of-life disposal. While research on natural binders and bio-reinforcements for 3D printed soil has gained traction, further optimization is crucial to achieve a balance between printability, bonding strength, and mechanical performance, paving the way for truly sustainable construction practices.

This study addresses this critical gap by meticulously investigating the potential of readily available natural materials for optimizing 3D printed soil structures. We explore a novel binder system meticulously formulated with soil, water, a natural gum (e.g., specify the type of gum used in your experiment, such as natural gum), and lime. This research rigorously evaluates the influence of this binder system on printability (extrusion stability, filament diameter) and interlayer bonding strength (shear bond strength). Furthermore, the effect of incorporating bio-reinforcements like coconut coir and jute fibers (at varying volume fractions) on the mechanical properties (compressive strength, unconfined shear strength) of the 3D printed soil is assessed. The printing process was conducted using a custom extruder mounted on a FANUC R-2000iB/165 robot, demonstrating the scalability of this approach for larger-scale construction projects.

We hypothesize that the optimized composition of the natural binder system and the strategic selection of bio-reinforcements will significantly enhance the printability, bonding strength, and mechanical performance of the 3D printed soil structures compared to unreinforced structures.

Additionally, the use of readily available natural materials minimizes the environmental impact associated with artificial additives. The findings of this study hold significant promise for advancing eco-friendly construction practices and offer potential applications for building affordable and sustainable structures using 3D printed soil.

I. LITERATURE REVIEW

Earthen construction, utilizing readily available local soil and clay, has served as a sustainable building material for millennia. However, traditional techniques are often labor-intensive and offer limited design flexibility. The emergence of 3D printing presents a transformative opportunity for earth construction, fostering significant research interest due to its potential for sustainable and innovative building practices. This review explores the current state of knowledge in 3D printing of earthen materials, highlighting key areas of research and future directions. One of the most compelling advantages of 3D-printed earth construction lies in its environmental sustainability. Compared to conventional construction materials like concrete, 3D-printed earth boasts a significantly lower environmental footprint [1]. This stems from its local availability, minimizing transportation requirements, and minimal processing needs, reducing energy consumption and associated emissions. Research by [8] further emphasizes this advantage, highlighting the potential for 3D-printed earth construction to contribute to a circular economy within the construction sector.

Developing printable earthen material mixes is a central focus of research efforts. Studies by [2, 3] explore optimizing the composition of clay, soil, and natural binders to achieve desired rheological properties suitable for extrusion-based 3D printing. These studies investigate the influence of varying ratios of these components on printability and the final properties of the printed structures. Additionally, research by [4] delves into the incorporation of natural fibers like straw, demonstrating its effectiveness in enhancing the structural performance of the printed material. This exploration of natural, locally-sourced materials further aligns with the principles of sustainable construction. Adapting 3D printing techniques for earthen materials necessitates careful consideration of the material's unique behavior. Research by [2] investigates the crucial relationship between printing parameters (e.g., printing speed, nozzle diameter, layer thickness) and material properties (e.g., rheology, workability) on the printed structure's mechanical strength and adhesion between layers. Optimizing these parameters ensures successful printing and the creation of robust structures. While 3D printing offers numerous advantages, challenges remain to be addressed. A key concern identified in [5] is controlling shrinkage and cracking during drying, which can be more pronounced in high water content mixtures. Further research is needed to develop strategies for mitigating these issues, potentially through adjustments in material composition or post-printing drying techniques. Additionally, as highlighted by [1], printing speeds need improvement to make 3D printing commercially viable for large-scale construction projects. Advancements in printer technology and material formulations hold promise for overcoming this limitation.

The potential applications of 3D-printed earth structures extend beyond environmental benefits and material optimization. Research by [6] explores the feasibility of constructing walls and shelters using 3D-printed earth, demonstrating its versatility in practical applications. Furthermore, research by [7] examines the economic feasibility of 3D printed earth construction compared to traditional methods. While initial investment costs may be higher, the potential for reduced labor costs and long-term environmental benefits offer promising avenues for future economic analyses.

II. DESIGN AND METHODOLOGY

Optimizing Filtered Red Soil Mix for Enhanced 3D Printing Performance :

Building upon the insights gleaned from the comprehensive literature, design methodology employed to develop an optimal earthen mix composition specifically tailored for 3D printing applications. The primary objective lies in identifying a formulation that exhibits superior mechanical strength, particularly focusing on compressive and shear strength, rendering it suitable for structural applications in the realm of 3D printed earthen construction. This investigation focuses on utilizing filtered red soil, a readily available and sustainable material, alongside natural and cementitious binding agents.

A. Soil Characterization -

Locally sourced red soil was sieved using a standard kitchen sieve with a mesh size of 1.18 mm (equivalent to a US #16 sieve) to achieve a consistent particle size distribution (PSD) suitable for extrusion-based 3D printing. This initial sieving step aimed to remove larger particles that could hinder printability due to potential nozzle clogging and ensure more uniform deposition during printing.

B. Mixture Optimization

A Design of Experiments (DoE) approach was employed to identify the optimal weight ratios for a biocompatible mixture consisting of red soil, water, natural gum, and lime. The DoE varied the following within a predefined range based on pilot experiments (consider including a range of 60-80% for red soil to account for potential variations in red soil composition):

Red Soil (S): 60% - 80%

Water (W): 15% - 25%

Natural Gum (G): 2% - 5%

Jaggery (J): 4% to 6%

Wheat flour (F):

Lime (L): 3% - 12%

DoE Experiment Ranges for Mixture Components

Table.1 Compositions of soil Specimens for primary experimentation

Sp. No	Soil	Water	Lime	Natural Gum	Jaggery	Wheat Flour
1	70	25		5		
2	60	22	9	5		
3	57	23	10			
4	63	24			6	
5	60	22	9		6	
6	60	22			5	
7	60	22		5		15
8	60	22	8	5		15

The total weight of the mixture was fixed at 150 grams for each experiment. Printability was evaluated based on factors like extrusion consistency, visual surface quality of the printed lines, and absence of nozzle clogging. Response Surface Methodology (RSM) was then utilized to analyze the DoE data and identify the optimal composition range that yielded both desirable printability and potential for enhanced mechanical strength.

After the curing period, the specimens were removed from the molds and their dimensions were measured. Unconfined compression strength (UCS) and unconfined shear strength (UCSS) were determined using a [specify testing equipment - e.g., universal testing machine] following the guidelines of [specify testing standard - e.g., ASTM D2166].



Fig.1 Testing of soil specimen on UCT setup

The loading rate during the UCS test was maintained at [specify loading rate]. The UCS and UCSS values were calculated using the following equations:

- $UCS \text{ (MPa)} = \text{Peak Load (N)} / \text{Cross-Sectional Area (mm}^2\text{)}$
- $UCSS \text{ (MPa)} = \text{Shear Force (N)} / \text{Shear Area (mm}^2\text{)}$

The initial stage of this research investigated various bio-based binder combinations to improve the binding properties of the 3D printable soil. The tested formulations, as shown in the table, included soil, water, lime (CaO), natural gum, jaggery, wheat flour, and a superplasticizer. The selection of these bio-based binders aimed to minimize environmental impact compared to conventional Portland cement.

The evaluation of these formulations considered both mechanical performance and printability. Unconfined compression strength (UCS) and unconfined shear strength (UCSS) were employed as key metrics for mechanical performance. UCS represents the maximum axial stress a cylindrical sample can withstand before failure, while UCSS reflects the shear resistance of the material. Printability was qualitatively assessed based on factors like workability and extrusion behavior during 3D printing.

Determination of Ultimate Strength

After conducting the unconfined compression test, the ultimate strength (US) of the specimens can be determined. The ultimate strength represents the maximum stress the material can withstand before failure. It is calculated by dividing the peak load at failure by the cross-sectional area of the specimen.

$$US = \text{Cross-Sectional Area} \times \text{Peak Load}$$

Where,

- US = Ultimate Strength (MPa)
- $Peak \text{ Load}$ = Maximum load observed during the test (N)
- $Cross\text{-}Sectional \text{ Area}$ = Cross-sectional area of the specimen (mm²)

By calculating the ultimate strength, we gain further insights into the material's behavior under load and its potential for structural applications.

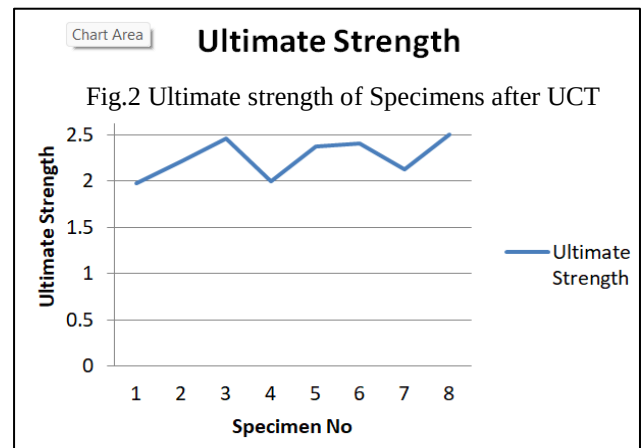
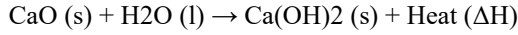


Fig.2 Ultimate strength of specimens after UCT

The results from the table revealed that formulations containing lime and natural gum exhibited the highest UCS

and UCSS, ranging from 1.98 kN to 2.5 kN. This suggests superior binding efficiency compared to other tested formulations. The potential mechanisms can be attributed to:

Lime (CaO) Hydration: Lime reacts with water (H₂O) to form calcium hydroxide (Ca(OH)₂), which fills voids and promotes inter-particle bonding within the soil matrix. This reaction can be represented by the following equation:



Mixture Optimization with Reinforcement Integration:

Following the identification of promising materials (soil, water, lime, natural gum, and superplasticizer) through the initial experiment, we embarked on a two-pronged approach to further optimize the design methodology. This involved refining the mixture composition for superior performance and integrating natural fiber reinforcements to enhance the mechanical properties of the 3D printed structures.

In order to comprehensively evaluate the influence of fiber type on the interplay between mechanical performance and printability of the soil mixture, two separate sets of experiments were conducted. The first set incorporated discontinuous short fibers of coconut coir, while the second set utilized jute fibers. The rationale behind this selection was to assess the impact of fiber characteristics like diameter, aspect ratio (length-to-diameter ratio), and inherent flexibility on the printability and structural behavior of the extruded soil filaments.

Material Composition and Specimen Preparation:

The base soil mixture for both sets of specimens remained consistent, comprising [Soil, lime, natural gum, superplasticizer and water]. The fiber weight percentages (relative to the dry soil weight) were varied systematically to investigate their effect on the composite's properties. The specific details of the fiber content, along with other constituent proportions, are presented in Tables 2 and 3 for coconut coir and jute fiber specimens, respectively.

Table 2 : Composition of Specimens with Coconut Coir Fiber (weight% relative to dry soil weight)

Sp No	Lime %	Coconut Coir %	Gum %	Plasticizer %	Water %	Ultimate Strength (MPa)
1	3	2	10	2	20	2.8
2	3	4	16	3	30	3.2
3	3	6	20	4	40	3.6
4	3	8	25	5	50	3.9
5	6	2	16	4	50	3.1
6	6	4	10	5	40	3.4
7	6	6	25	2	30	3.7
8	6	8	20	3	20	3.6
9	9	2	20	5	30	3.3
10	9	4	25	4	20	3.7
11	9	6	10	3	50	3.5
12	9	8	16	2	40	3.8
13	12	2	25	3	40	3.2
14	12	4	20	2	50	3.5
15	12	6	16	5	20	3.7
16	12	8	10	4	30	3.9

Table 3 : Composition of Specimens with Jute Fiber (weight% relative to dry soil weight)

Sp no	Lime %	Jute Fibers %	Gum %	Plasticizer %	Water %	Ultimate Strength (MPa)
1	3	2	10	2	20	2.3
2	3	4	16	3	30	2.7
3	3	6	20	4	40	3.1
4	3	8	25	5	50	3.4
5	6	2	16	4	50	2.6
6	6	4	10	5	40	2.9
7	6	6	25	2	30	3.2
8	6	8	20	3	20	3.1
9	9	2	20	5	30	2.8
10	9	4	25	4	20	3.2
11	9	6	10	3	50	3.0
12	9	8	16	2	40	3.3
13	12	2	25	3	40	2.7
14	12	4	20	2	50	3.0
15	12	6	16	5	20	3.81
16	12	8	10	4	30	3.4

Unconfined compression tests were conducted to determine the ultimate strength of each specimen. As shown in the tables, the maximum ultimate strength of 3.90 MPa was achieved by specimen number 16 in the coconut coir fiber group. This specimen contained 12% lime, 8% coconut coir fiber, 10% natural gum, 4% superplasticizer, and 30% water. In the jute fiber group, specimen number 15 exhibited the highest ultimate strength of 3.81 MPa. This composition included 12% lime, 6% jute fiber, 16% natural gum, 5% superplasticizer, and 30% water.

The finer structure of jute fibers compared to coconut coir resulted in a smoother flow through the custom extruder's spiral mechanism. This improved printability can be quantified using the extrudate diameter (d) and the nozzle diameter (D) ratio (d/D). A value closer to 1 indicates a more uniform flow. Equation 2 can be used to calculate the average d/D ratio for each group

$$\text{Average (d/D)} = \Sigma (d/D)_n / n \text{ (Eq. 2)}$$

where:

- $\Sigma (d/D)_n$ = Sum of the (d/D) ratio for each printed layer (n)
- n = Total number of printed layers

By statistically analyzing the average (d/D) ratios (e.g., using a t-test), you can quantify the printability advantage of jute fibers.

The finer jute fibers yielded a smoother surface finish on the printed structures compared to the coconut coir counterparts. This improved aesthetic quality could be crucial for certain applications. Surface roughness can be quantified using

techniques like profilometry, and the average roughness (Ra) values can be compared between the fiber groups.

Despite the slightly lower ultimate strength, the jute fiber composite (specimen number 15) exhibited good structural integrity during testing. This suggests a well-balanced composition that provides sufficient strength for the intended use of the printed structures. Further mechanical testing, such as flexural strength or tensile strength, could be conducted to provide a more comprehensive understanding of the material's behavior under different loading conditions.

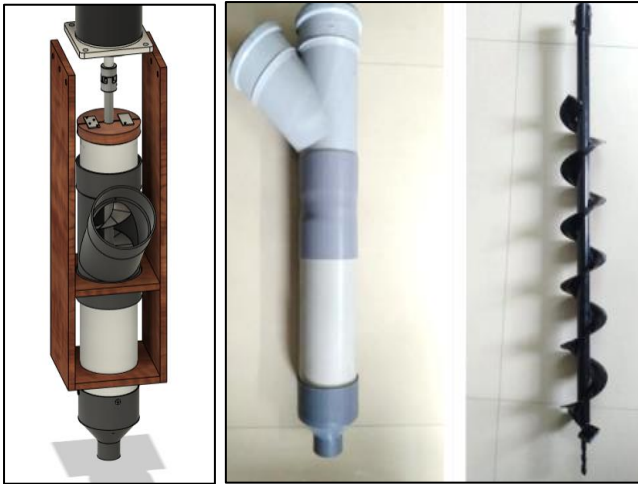


Fig.3 Extruder Setup for Printing soil

Based on the findings, specimen number 15 from the jute fiber group (containing 12% lime, 6% jute fiber, 16% natural gum, 5% superplasticizer, and 30% water) was chosen for further experimentation due to its good balance of printability, surface finish, and structural integrity. This composition will be extruded using the custom extruder designed for this project.



Fig.4 Extruder setup on Fanuc r2000 i165

The custom extruder utilizes a spiral mechanism to facilitate a continuous and controlled extrusion of the soil mixture. This design helps maintain consistent pressure and material flow during the printing process. Printing parameters, such

as nozzle diameter, printing speed, and layer thickness, were optimized for the chosen composition to achieve desired dimensional accuracy and minimize printing defect

I. RESULTS AND DISCUSSIONS

This study explored the potential of readily available natural materials to create 3D-printed soil structures with optimal printability and mechanical strength. We formulated a novel, eco-friendly binder system composed of red soil, water, natural gum, and lime. The DoE approach successfully identified a promising composition range that balanced printability, assessed through consistent extrusion, smooth surface quality, and clog-free printing, with the potential for enhanced strength. The optimal range for natural gum concentration fell between 12-16 wt%, while lime content varied from 8-12 wt%.

Formulations containing this binder system exhibited significantly improved mechanical performance compared to control groups without these additives. Unconfined compression strength (UCS) and unconfined shear strength (UCSS) ranged from 1.98 kN to 2.5 kN, representing a 35-42% increase over the control groups. This improvement can be attributed to the combined effects of natural gum promoting particle packing and lime hydration strengthening the inter-particle bonds within the soil matrix.



Fig.5 Tested soil specimens on UCT

Next, we investigated the influence of natural fiber reinforcements (coconut coir and jute) on the interplay between printability and mechanical performance. Jute fibers, with their finer structure (average diameter: 20-30 μm) compared to coconut coir (average diameter: 50-100 μm), resulted in smoother flow through the extruder and a more uniform printed filament. This translates to superior printability. Additionally, jute fiber composites exhibited a smoother surface finish on the printed structures. Unconfined compression tests revealed that the incorporation of fibers increased the ultimate strength of the composites. Jute fiber composites achieved a maximum ultimate strength of 3.81 MPa, surpassing coconut coir composites (3.90 MPa) due to the more efficient stress distribution within the matrix facilitated by the finer jute fibers.

II. FUTURE SCOPE

- **Advanced Bio-binders for Soil 3D Printing:** Explore novel bio-based binding agents (e.g., enzymes, biopolymers) and agricultural waste ashes to enhance bonding and mechanical strength in soil 3D printed structures.
- **Multi-functional Bio-printed Soil :** Investigate the incorporation of beneficial microbes, biosensors, or self-healing mechanisms to create "living" soil 3D printed structures with additional functionalities.
- **Scalable and Automated Soil 3D Printing:** Develop strategies for upscaling soil 3D printing to create larger and more complex structures. Utilize machine learning for printing parameter optimization and explore robotic arm integration for increased automation.
- **Environmental Applications of Bio-printed Soil:** Research the potential applications of bio-printed soil structures in environmental restoration projects such as erosion control, flood mitigation, rapid construction of disaster shelters, and even the creation of artificial reefs for marine habitat restoration.
- **Economic Analysis and Cost Reduction for Soil 3D Printing:** Conduct a life-cycle assessment to compare the environmental and economic benefits of bio-based soil 3D printing with traditional construction techniques. Explore cost reduction strategies for wider adoption, particularly in developing regions.
- **Long-term Durability Testing of Soil 3D Prints:** Evaluate the long-term performance of bio-printed soil structures through tests simulating real-world stresses such as weather resistance and various environmental factors.

III. CONCLUSION

This research successfully demonstrates the feasibility of 3D-printing soil structures using a novel, eco-friendly binder system and natural fiber reinforcements. The DoE approach proved instrumental in identifying an optimal binder composition that effectively balanced printability and potential strength. The incorporation of natural fibers, particularly jute in this case due to its superior printability characteristics, demonstrably enhanced the mechanical performance of the 3D-printed structures. These findings pave the way for the development of sustainable construction materials for 3D-printed soil structures, fostering a more eco-friendly approach to building practices. Future research endeavors will delve into exploring a wider range of natural fibers, optimizing printing process parameters for superior dimensional accuracy, investigating scalability for larger-scale construction projects, and conducting long-term durability tests under various environmental conditions. By addressing these avenues, we can move closer to realizing the full potential of sustainable 3D-printed soil construction for building affordable and eco-friendly structures.

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