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Research Article

Improving bond performance of 3D-printable earth-based mortar reinforced with jute fibers

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ABSTRACT

3D printing technology has transformed the construction industry by enabling rapid and cost-effective production of complex geometries. However, it faces significant challenges, including sustainability concerns due to cement's environmental impact and reinforcement issues arising from the incompatibility of traditional steel. These challenges necessitate the development of innovative material solutions. This study aims to enhance the bond strength between sustainable earth-based mortar and jute fibers used as reinforcement in 3D printed structures by exploring the effects of different treatments and compositions. Bond strength was evaluated by considering the effect of different treatments on the resistance of the fiber to being pulled out of the mortar. Pull-out tests were conducted on specimens with varying compositions and treatments. Results demonstrated substantial improvement in bond performance; specifically, the reference sand-free earth-clay mortar exhibited the lowest interfacial shear strength of 0.30 MPa. The most remarkable enhancement was observed in specimen which jute fibers pre-treated by immersion in mud slurry, which showed a 147% increase, reaching an interfacial shear strength of 0.74 MPa. Combining sand addition and fiber pre-treatment, however, did not yield additional benefits. These results indicate that simple, cost-effective local treatments can notably enhance fiber-matrix bond strength in 3D-printed earth-based structures without necessitating additional equipment or significant expense.

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1. Introduction

The construction industry contributes significantly to environmental problems such as high CO_2 emissions, depletion of natural resources, and intensive energy consumption, especially due to the calcination process of cement production (Mahmud et al. 2025; Mohamad et al. 2025; Bulut 2024; Güney and Yıldızel 2024; Macherla 2023; Melià et al. 2014). In response, earth-based materials are increasingly being considered due to their environmental friendliness and lower energy requirements for production. Recent studies have focused on improving the engineering properties and durability of these natural materials (Nagaraj and Muguda 2020). This renewed interest is in line with broader trends towards sustainable construction practices, as evidenced by the growing popularity of materials such as rammed earth (Sposito and Scalisi 2017).

3D printing technology has emerged as a promising method in the construction industry, allowing for rapid production, cost savings, and intricate architectural designs. Its integration with earth-based materials has attracted considerable attention due to their sustainability and accessibility (Shahrubudin et al. 2019; Ferretti et al.

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2022; Gomaa et al. 2021; Perrot et al. 2016; Tarhan and Perrot 2023; Tarhan et al. 2024). Perrot et al. (2016) pioneered the field of 3D-printable earth-based materials, successfully demonstrating the 3D printability of earth-based mixtures for the first time. Gomaa et al. (2021) developed a novel dual-ram extruder system for 3D printing cob, improving extrusion rate, continuity, consistency, and mobility while also optimizing the cob mixture for 3D printing by adjusting water content. Ferretti et al. (2022) investigated the long-term mechanical properties of earthen mixtures for 3D printing, examining the effects of rice husk shredding on compressive strength and stiffness.

However, reinforcement is a significant challenge that needs to be addressed but is mainly ignored in 3D-printable earth-based materials. Natural fibers such as jute (Loccarini 2017; Sen and Saha 2024; Tarhan and Perrot 2023; Tarhan et al. 2024), sisal (Alves Fidelis et al. 2013; Yadav et al. 2019; Zavaleta et al. 2024), date palm (Abdeldjebar et al. 2018; Benzerara et al. 2021; Dawood and Alqaissi 2024; Taallah and Guettala 2016), and bamboo (Sen and Saha 2024) are utilized to enhance the mechanical properties of earth-based construction materials. Nevertheless, the bond between such fibers and clay-rich printable mortars remains a key limitation, often leading to inadequate stress transfer and reduced structural efficiency.

Taallah and Guettala (2016) examined untreated and alkali-treated date palm fibers in compressed earth blocks. Alkali treatment slightly improved fiber performance but decreased overall block strength and thermal insulation compared to non-fiber blocks. The study highlights the complex effects of fiber treatments on earth-based materials. Ramesh et al. (2017) also examine the use of plant fibers in construction, noting their potential in composites for sustainable development and the improved mechanical properties they can provide. Loccarini et al. (2017) investigated using jute fabric as a natural reinforcement for rammed earth structures. The study examined the adhesion capacity of jute fabric with an earth-gypsum matrix through peeling tests and single lap joint tests. Results showed that jute fabric reinforcement significantly increased the bearing capacity and kinematical ductility of rammed earth arches. Tarhan and Perrot (2023) proposed a novel technique using untreated jute fabric to reinforce 3D-printed earth-based composites. They found that jute fabric reinforcement significantly improved the ductility and compressive strength of 3D-printed earth-based samples. In a follow-up study, Tarhan et al. (2024) investigated the effects of earth slurry-treated jute fibers on the flexural, compressive, and interlayer strength of 3D-printed earth-based beam samples. This treatment resulted in notable improvements in mechanical properties, highlighting the significant impact of fiber treatment on the performance of reinforced 3D-printed earth-based materials. The study also emphasized that further measures should be investigated to increase the bond strength of jute fabric and earth-based mortar. Sen and Saha (2024) evaluated bitumen-treated jute and bamboo fibers for retrofitting rammed earthen houses against seismic loads. Their novel approach using bitumen-treated bamboo strips as external reinforcement and L-shaped corner reinforcements significantly enhanced structural strength and ductility, with seismic resistance improving up to 6.81 times compared to unreinforced structures. However, Archila et al. (2018) noted that while plant fibers can improve certain material properties, they may also introduce new complexities that necessitate further research and innovation.

Although previous studies have investigated the use of natural fibers in earth-based construction materials, there is still a limited understanding of how these fibers interact with earth-based mortar specifically in the context of 3D-printed structures. In particular, the mechanisms governing fiber-matrix bonding and the influence of fiber treatments in 3D printing remain largely unexplored. Addressing this gap, the present study aims to examine the key factors that influence the bond strength between jute fibers and 3D-printable earth-based mortars. To achieve this, jute fibers were pre-treated by immersion in clay (mud) slurry - the binder component of the mortar - before being placed between printed layers. Pull-out tests were then conducted to assess the bond strength of both untreated and slurry-treated fibers in two different mortar compositions. By doing so, this research contributes new quantitative insights into how sand addition and fiber pre-treatment affect interfacial bonding, thereby advancing the material design of sustainable, fiber-reinforced 3D-printed structures.

2. Materials and Method

This section details the materials used in the study, the preparation of specimens, and the methods employed for testing bond strength between jute fibers and earth-based mortars. The focus is on two main variables: the composition of the earth-based mixture and the pre-treatment of jute fibers.

2.1. Materials

In the current study, the same natural materials used in previous studies (Tarhan and Perrot 2023; Tarhan et al. 2024) were adopted to prepare the earth-based mortar mixtures. These include silt-containing raw earth, clay-rich quarry wash mud, and fine silica sand with a maximum particle diameter of 1 mm and a bulk density of 2.26 g/cm^3. The quarry wash mud, acting as the main binder, had a specific surface area of 10 m^2/g, a density of 2.65 g/cm^3, a plasticity index of 29, a liquid limit of 62.8%, and a plastic limit of 34.1%. To evaluate the influence of sand, a second sand-free mixture was also prepared, replicating the formulation reported by Tarhan et al. (2024) but omitting silica sand. Since sand represents the largest particle size fraction in the mixture, its inclusion was expected to prominently affect fiber-mortar interaction, especially considering the small dimensions of the pull-out test specimens. Compositions for both mixtures are listed in Table 1.

The jute fibers used were natural, untreated, and sourced commercially. For the treatment group, fibers were immersed in a clay (mud) slurry for 15 minutes, then gently wiped to remove excess slurry and dried at ambient conditions (20 °C, ~50% RH) for 24 hours. Specimens were classified into four groups as shown in Table 2.

Table 1. Proportions of the mixtures.

3D printable mixes	Components (%)			
	Raw earth	Quarry wash	Sand	Water
1. Mixture (with sand)	44	16	40	21
2. Mixture (sand-free)	64	36	-	28

Table 2. Description of the specimen groups based on mixture composition and fiber treatment.

Group	Mixture composition	Fiber treatment
EC-F	Earth + Clay (No Sand)	Untreated
EC-MF	Earth + Clay (No Sand)	Mud slurry–treated
ECS-F	Earth + Clay + Sand	Untreated
ECS-MF	Earth + Clay + Sand	Mud slurry–treated

To assess the printability of both mixtures, fall cone tests were conducted in accordance with EN ISO 17892-6 (2017). This was achieved by measuring the penetration depth of a cone under an applied load. The cone tip was placed on the surface of the mixture and released for approximately five seconds, allowing sufficient time for penetration to occur. The resulting data demonstrated penetration depths of 19.8 mm for the sand-blended mix and 16.5 mm for the sand-free mix. Both of these mixtures exhibited excellent printability characteristics for use in 3D printing. Fig. 1 shows one of the 3D-printed beam-shaped samples reinforced with jute textiles.

Fig. 1. Earth-based specimens equipped with 3D-printed jute fabric (Tarhan and Perrot 2023).

Fiber diameters –both untreated and slurry-coated– were measured using an optical microscope (Leica DM750), and representative images are provided in Fig. 2. Eight jute fiber samples were utilized in sand-blended and sand-free mixes, untreated, and immersed in mud slurry for the pull-out test. Some of the fiber diameters measured by optical microscopy are shown in Fig. 2.

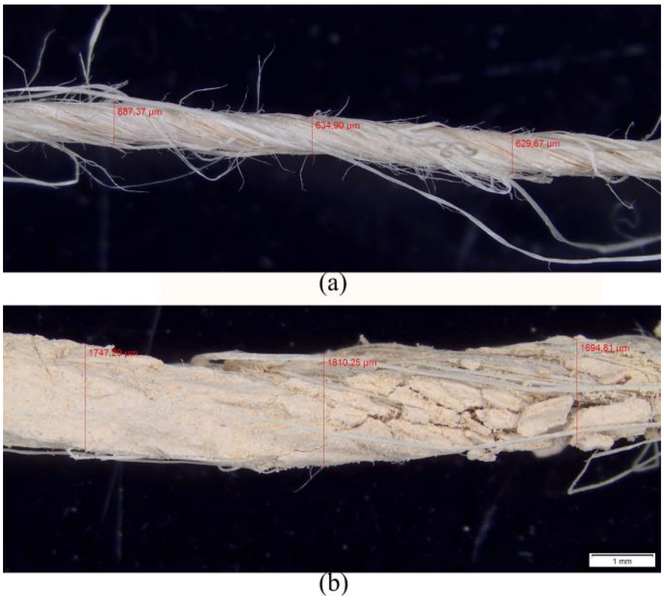

Fig. 2. Optical microscope measurements: (a) Diameter of the untreated jute fiber; (b) Jute fiber immersed in mud slurry.

2.2. Sample preparation and pull-out test

Pull-out test specimens were prepared using a custom designed PVC mould as shown in Fig. 3. The mould consists of two laser-cut PVC plates: the lower plate contains a 1 mm diameter hole to center the fiber, the upper plate forms a 5 mm diameter cylindrical cell for the earth mixture. Prior to casting, the upper mold surfaces were lubricated with a thin layer of Vaseline to facilitate demolding. The jute fiber was threaded through the mold hole and centered so that approximately 15 mm of its length was embedded. The earth-based mixture was then poured into the mold and gently compacted by hand. After casting, the specimens were left in the mold for 24 hours under laboratory conditions (20 °C and 50% relative humidity). They were then demolded and further oven dried at 60 °C for 15 days to ensure complete moisture removal and strength gain, following the methodology of Tarhan and Perrot (2023).

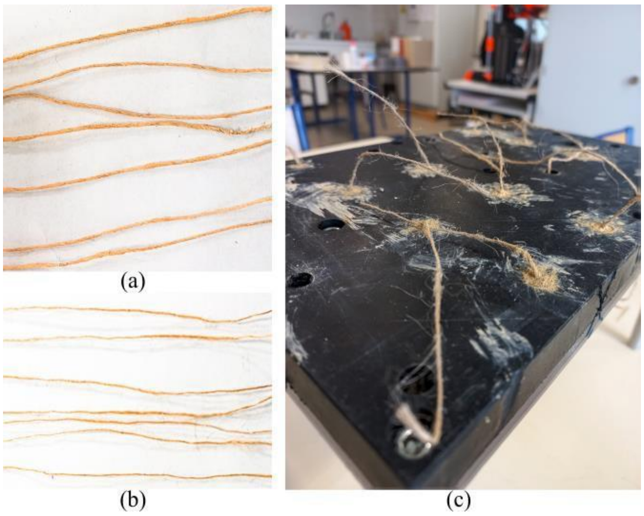

Fig. 3. (a) Muddy jute fibers; (b) Untreated jute fibers; (c) The tool used to create specimens, and placing jute fiber and earth-based mortars.

For mechanical testing, tensile tests were performed using a universal testing machine (MTS Insight Series) equipped with a 50 N load-cell. Each jute fiber was clamped in pneumatic grips to prevent slippage and pulled at a constant displacement rate of 1 mm/min until complete debonding occurred. Testing was carried out under controlled laboratory conditions (~20 °C, 50% RH). The average interfacial bond strength was considered as the apparent interfacial shear strength (*IFSS*), assuming a uniform interfacial stress distribution at the fiber/earth interface. It was calculated according to Lecompte et al. (2015) using the Eq. (1):

$$IFSS = \frac{F_{bond}}{\pi . t . D_f} \quad (1)$$

where F_{bond} is the maximum pull-out force (N), t is the matrix height (mm), and D_f is the average fiber diameter (mm) placed in the earth-based mixture (Fig. 4). This calculation provides a standardised measure of interfacial bonding performance, allowing comparison between different mixture compositions and fiber treatments, and is critical for understanding the efficiency of load transfer between the fiber and the surrounding matrix.

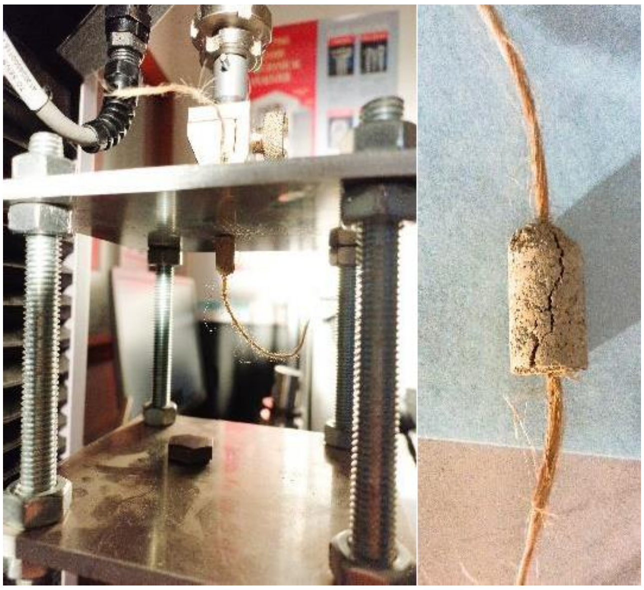

Fig. 4. Pull-out test device and crack development in the sample.

3. Results and Discussion

Table 3 and Fig. 5 present the results from the pull-out test, including maximum force, maximum elongation, *IFSS*, and the percentage increase in bond strength compared to the reference EC-F specimens.

Table 3. Results of the pull-out test.

Group	Sample name	Force (N)	Extension (mm)	*IFSS* (MPa)	Average *IFSS* (MPa)	Increase (%)
1	EC-F (1)	5.42	1.58	0.33	0.30	-
	EC-F (2)	4.29	1.43	0.26		
2	ECS-F (1)	8.54	1.38	0.52	0.57	90
	ECS-F (2)	9.96	1.45	0.61		
3	EC-MF (1)	13.64	2.17	0.84	0.74	147
	EC-MF (2)	10.50	1.57	0.64		
4	ECS-MF (1)	9.56	2.55	0.59	0.56	87
	ECS-MF (2)	8.47	1.03	0.52		

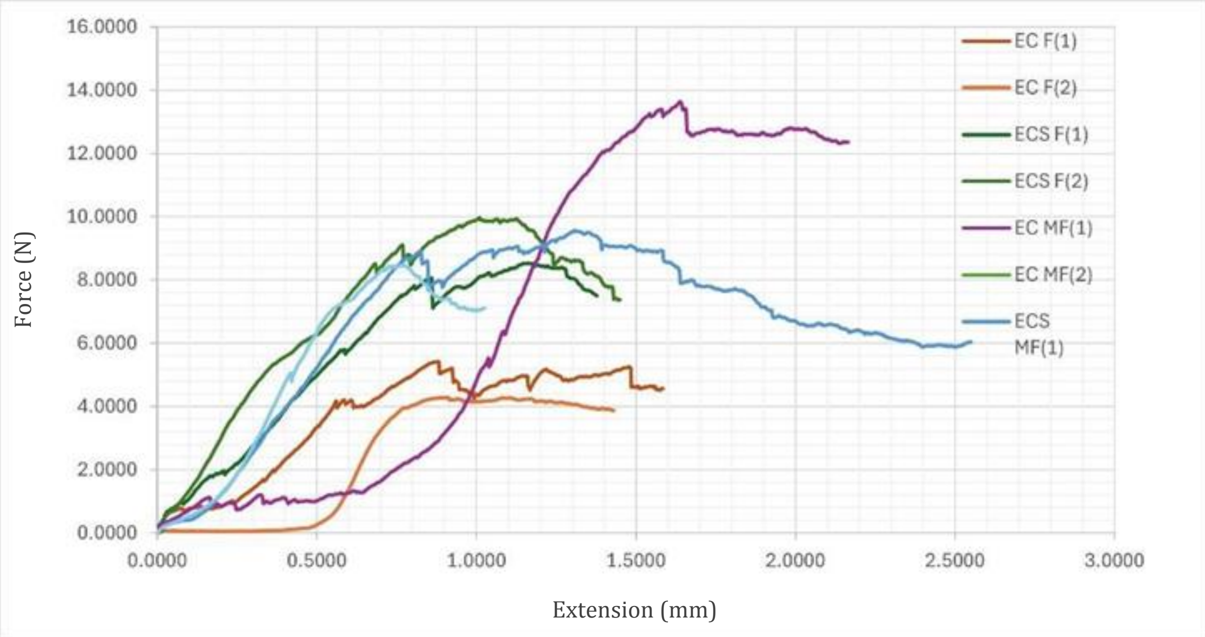

Fig. 5. Pull-out test results.

The reference group (EC-F), consisting of earth and clay without sand and using untreated jute fiber, showed the lowest average *IFSS* at 0.30 MPa. The addition of sand to the mix (ECS-F) resulted in a significant 90% increase to 0.57 MPa. This improvement is probably due to the increased frictional resistance provided by the sand particles at the fiber-matrix interface. The presence of sand can create a more tortuous path during fiber extraction, increasing the mechanical interlock and the energy required for debonding – defined here as the resistance of the fiber to being pull-out of the mortar. These findings are consistent with the findings of Tang et al. (2010), who demonstrated that increasing sand content in soil composites improved sliding resistance of fibers due to higher superficial roughness. Similarly, Abdi et al. (2011) showed that encapsulating reinforcement in sand layers within clay matrices significantly increased pull-out resistance.

The most significant improvement was observed in the EC-MF group where the jute fibers were pre-treated by immersion in clay slurry. This group achieved an average *IFSS* of 0.74 MPa, an increase of 147% over the reference. Two main mechanisms may explain this improvement: (i) the clay slurry may fill micro voids on the fiber surface, increasing the effective contact area; and (ii) the pre-treatment may improve the physico-chemical compatibility between the fiber and the clay-based matrix, resulting in a stronger bond. Similar positive effects of slurry treatments were reported by Tarhan et al. (2024), who found that jute fibers treated with earth slurry improved both flexural and compressive strength in 3D printed earth-based elements. Fagone et al. (2019) showed that jute fabric reinforcement improved adhesion and ductility in rammed-earth arches, although bond strength was not quantified in this study. Fode et al. (2025) revealed that bentonite slurry-treated sisal fibers embedded in cementitious matrices exhibited improved interfacial bonding and mechanical strength.

Interestingly, the combination of sand addition and fiber pre-treatment (ECS-MF) resulted in an average *IFSS* of 0.56 MPa, an increase of 87% over the reference. However, this was slightly less than the improvement achieved by pre-treatment alone (EC-MF), suggesting that the effects of the two methods may not be additive. A possible explanation is that there may be opposing mechanisms at work. While sand increases friction and surface roughness at the interface, the slurry coating may smooth or modify the fiber surface, thereby reducing the ability of the matrix to compact tightly around the treated fibers. In addition, material-specific limitations –such as the binding capacity of the clay matrix or the tensile strength of the jute fiber– may impose a ceiling beyond which further improvements are not possible, even with multiple interventions. This interpretation is consistent with Archila et al. (2018), who noted that combining reinforcement strategies in earthen materials can lead to complex interactions that do not necessarily yield cumulative benefits.

These results demonstrate that both sand addition and fiber surface treatment can significantly improve fiber-matrix bonding, but clay slurry treatment emerges as a more effective strategy, particularly for small-scale 3D printing applications. Importantly, the performance of the sand-free, fiber-treated group (EC-MF) highlights a simple and innovative approach that relies solely on readily available, low-cost materials without the need for sand or advanced processing. This makes the method highly relevant for sustainable construction, particularly in regions where sand is scarce or expensive.

4. Conclusions

This study investigates the bonding between jute fiber and earth-based 3D printable mortar via pull-out tests on different fiber conditions (untreated and mud slurry-treated) and mixture compositions.

The results indicate that interfacial shear strength can be substantially improved -from 0.30 MPa to 0.74 MPa (a 147% increase) - through clay slurry treatment of jute fibers, offering an accessible and cost-effective reinforcement method. Although sand addition alone led to a 90% increase, combining both strategies yielded no further improvement, suggesting a performance ceiling likely governed by material limits. These findings highlight the effectiveness of targeted, single interventions in enhancing fiber–matrix interaction and offer practical guidance for optimizing the mechanical performance of sustainable, 3D-printed earthen structures.

However, it was found that when the fibers were pretreated, the presence of sand may inhibit further bond development - possibly due to reduced matrix compaction around the slurry-coated fibers or interference with the formation of a continuous contact layer at the fiber-matrix interface, both of which may limit mechanical interlocking and adhesion. Future research should focus on evaluating the long-term durability of fiber-reinforced earth mortars, particularly their resistance to moisture ingress, thermal cycling, and freeze-thaw conditions, as these factors are critical to ensuring structural integrity and service life in real-world applications. Furthermore, an important finding is that the sand content may be critical for applications requiring sufficient bond strength. Hence, further investigation is necessary to optimize the amount of sand needed. In addition, it is suggested that future studies evaluate long-term bond retention through accelerated ageing cycles and verify the effectiveness of treated fibers in full-scale 3D-printed wall panels.

This study contributes to the advancement of sustainable 3D printing technology by demonstrating that simple, low-cost fiber treatments and earth-based mortar formulations can significantly improve fiber-matrix bonding without the need for synthetic additives or complex processing – providing a viable pathway to environmentally friendly and locally adaptable construction solutions.

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Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

References

Abdeldjebar R, Hamouine A, Fouchal F, Labbaci B, Zebair A (2018). Effects of treated date palm fiber on durability of stabilized earth blocks (SEB). *International Journal of Civil Engineering and Technology*, 9(5), 293–305.

Abdi MR, Arjomand MA (2011). Pullout tests conducted on clay reinforced with geogrid encapsulated in thin layers of sand. *Geotextiles and Geomembranes*, 29(6), 588–595.

Alves Fidelis ME, Vitorino Castro Pereira T, da Fonseca Martins Gomes O, de Andrade Silva F, Dias Toledo Filho R (2013). The effect of fiber morphology on the tensile strength of natural fibers. *Journal of Materials Research and Technology*, 2(2), 149–157.

Archila H, Kaminski S, Trujillo D, Zea Escamilla E, Harries KA (2018). Bamboo reinforced concrete: A critical review. *Materials and Structures/Materiaux et Constructions*, 51, 1–18.

Benzerara M, Guihéneuf S, Belouettar R, Perrot A (2021). Combined and synergic effect of Algerian natural fibres and biopolymers on the reinforcement of extruded raw earth. *Construction and Building Materials*, 289, 123211.

Bulut H (2024). A different approach for green concrete production: Determination of the effect of e-waste and waste rubber powder on durability properties of concrete. *Challenge Journal of Concrete Research Letters*, 15(3), 69–81.

Dawood ZM, Alqaissi ZH (2024). Impact of date-palm fibers on fine soil's compaction and strength properties. *Journal of Engineering*, 30, 67–82.

EN ISO 17892-6 (2017). Geotechnical investigation and testing – laboratory testing of soil – Part 6: Fall cone test. European Committee for Standardization, Brussels, Belgium.

Fagone M, Kloft H, Loccarini F, Ranocchiai G (2019). Jute fabric as a reinforcement for rammed earth structures. *Composites Part B: Engineering*, 175, 107064.

Ferretti E, Moretti M, Chiusoli A, Naldoni L, de Fabritiis F, Visonà M (2022). Rice-husk shredding as a means of increasing the long-term mechanical properties of earthen mixtures for 3D printing. *Materials*, 15(3), 743.

Fode TA, Jande YA C, Kim YD, Ham MG, Lee J, Kivevele T, Rahbar N (2025). Effects of different lengths and doses of raw and treated sisal fibers in the cement composite material. *Scientific Reports*, 15(1), 1603.

Gomaa M, Jabi W, Veliz Reyes A, Soebarto V (2021). 3D printing system for earth-based construction: Case study of cob. *Automation in Construction*, 124, 103577.

Güney B, Yıldızel S (2024). Optimization of mechanical properties in lime-based composites using the Taguchi method. *Challenge Journal of Structural Mechanics*, 10(3), 109-115.

Lecompte T, Perrot A, Subrianto A, Le Duigou A, Ausias G (2015). A novel pull-out device used to study the influence of pressure during processing of cement-based material reinforced with coir. *Construction and Building Materials*, 78, 224–233.

Loccarini F (2017). Behaviour of Rammed Earth Structures: Sustainable Materials and Strengthening Techniques. *Ph.D.* thesis, University of Braunschweig, Braunschweig, Germany & University of Florence, Firenze, Italy.

Macherla URT (2023). A survey study on challenges and factors affecting in adopting sustainable construction methods in Indian construction industry. *MATEC Web of Conferences*, 384, 01004.

Mahmud H, Ahmed T, Islam MS (2025). Combined effect of rice husk ash and animal bone powder on strength and permeability of concrete. *Challenge Journal of Structural Mechanics*, 11(1), 1–13.

Melià P, Ruggieri G, Sabbadini S, Dotelli G (2014). Environmental impacts of natural and conventional building materials: A case study on earth plasters. *Journal of Cleaner Production*, 80, 179–186.

Mohamad N, Embong R, Othman NH, Muthusamy K, Jaafar MFM (2025). Flowability and compressive strength of ternary blended cement mortar of coal bottom ash and ground cockle shell ash. *Challenge Journal of Concrete Research Letters*, 16(1), 25–32.

Nagaraj HB, Muguda S (2020). Recent innovations in stabilized earthen construction. In: *Sustainable Materials in Building Construction*, Springer, Cham, 149–164.

Perrot A, Rangeard D, Pierre A (2016). Structural built-up of cement-based materials used for 3D-printing extrusion techniques. *Materials and Structures*, 49, 1213–1220.

Ramesh M, Palanikumar K, Reddy KH (2017). Plant fibre based bio-composites: Sustainable and renewable green materials. *Renewable and Sustainable Energy Reviews*, 79, 558–584.

Sen B, Saha R (2024). Structural stability evaluation of natural fiber retrofitted low-cost rammed earthen houses under seismic loading. *Structural Engineering International*, 35(2), 286–305.

Shahrubudin N, Lee TC, Ramlan R (2019). An overview on 3D printing technology: Technological, materials, and applications. *Procedia Manufacturing*, 35, 1286–1296.

Sposito S, Scalisi F (2017). Sustainable architecture: The eco-efficiency earth construction. *European Journal of Sustainable Development*, 6(4), 246–254.

Taallah B, Guettala A (2016). The mechanical and physical properties of compressed earth block stabilized with lime and filled with untreated and alkali-treated date palm fibers. *Construction and Building Materials*, 104, 52–62.

Tang CS, Shi B, Zhao LZ (2010). Interfacial shear strength of fiber reinforced soil. *Geotextiles and Geomembranes*, 28(1), 54–62.

Tarhan Y, Perrot A (2023). Reinforcement of 3D printable earth-based mortar with natural textile material. *Materials Today: Proceedings*, In Press.

Tarhan Y, Tarhan İH, Jacquet Y, Perrot A (2024). Mechanical behaviour of 3D printed and textile-reinforced eco-friendly composites. *Journal of Sustainable Cement-Based Materials*, 14(3), 477–495.

Yadav MEK, Kishore PR, Kumar AS, Swetha Sri AS (2019). Influence of sisal fibers on the properties of rammed earth. *International Journal of Innovative Technology and Exploring Engineering*, 8, 663–667.

Zavaleta D, Ñañez R, Silva G, Ruiz G, Pando MA, Aguilar R, Nakamatsu J, Kim S (2024). Additive construction using enhanced earthen-based composites: Improvement of the mechanical strength and water durability using chitosan and agave fibers. *Construction and Building Materials*, 411, 134159.