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Reinforcement of 3D printable earth-based mortar with natural textile material

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A R T I C L E I N F O

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A B S T R A C T

Earth-based building materials, used in the construction industry for centuries, have gained renewed interest due to the increasing environmental threats posed by cement-based materials. These earth-based materials offer many advantageous features such as affordability, easy accessibility, recyclability resulting in zero waste, indoor climate control, and breathability, making them indispensable for sustainable development. The emergence of 3D printing technology has brought revolutionary benefits to the construction sector, enabling rapid, cost-effective, and eco-friendly production while offering almost unlimited design possibilities. However, the challenge of reinforcement remains a critical issue that requires solutions in 3D printed technology in construction. Mainly, the complexities of 3D-printed geometries make traditional construction reinforcement methods more challenging to apply. This study proposes a technique to address the reinforcement challenges of 3D printing technology using natural materials. Earth-based samples produced through 3D printing were reinforced with textiles, specifically natural jute fabric. The effectiveness of this approach was investigated, focusing on beam-shaped samples designed for experimental studies. The samples comprised a 3D printable mixture containing only clay, earth, and sand, reinforced with natural jute fabric textile. The findings of this research emphasise the positive impact of reinforcing 3D printable earth-based composites with natural jute fabric textiles, resulting in a structural material with enhanced compressive strength, good tensile strength, and ductile behaviour.

1. Introduction

Earth-based materials, including adobe, cob, and rammed earth, hold significant importance due to their superior sustainability and environmentally friendly nature compared to cement-based materials. These materials are crafted from natural, locally available components, and their production does not necessitate energy-intensive manufacturing processes [1]. Moreover, earth-based materials offer a cost-effective alternative to cement-based materials, particularly when sourced locally [2].

One of the most recent trends in the construction industry is adopting digital-based construction methods, notably 3D printing. This technology enables accelerated production rates, fosters more economical and eco-friendly construction practices, enhances worker safety, and provides greater design freedom [3]. Earth-based materials, such as clay and soil, can be effectively utilised in 3D printing to create structures akin to concrete. This innovative technique has the potential to revolutionise the construction sector, facilitating swift on-site building and other structure production using locally-sourced and sustainable materials.

However, the application of 3D printing also presents technical challenges, particularly concerning reinforcement. Upon examining the literature on this subject, various reinforcement solutions have been proposed for 3D printable concretes derived from cement-based materials. Some of these suggestions include adding fibres to the 3D printable concrete mixture [4,5,6,7,8], using 3D printed concrete as a mould and incorporating vertical reinforcement within the mould [9], and employing multiple arms to print both reinforcement and concrete [10]. On the other hand, using earth-based mortars in 3D concrete technology is still relatively new, leading to limited research on the reinforcement of 3D-printed earth-based mortars. Further exploration and investigation are needed to develop effective reinforcement techniques for earth-based 3D concrete.

Using a high-performance fibre grid embedded in an inorganic matrix to reinforce structures externally is commonly known as Textile Reinforced Mortar (TRM) or Fabric Reinforced Cementitious Matrix

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(FRCM). Textile materials have been recognised for their ability to enhance cement matrices' mechanical behaviour significantly, exhibiting superior tensile strength, toughness, ductility, energy absorption, and resistance against environmental degradation [11]. According to Scheurer et al. [12], continuous fibre-based reinforcements (textiles) offer a promising and versatile alternative for reinforcing 3D-printed cement-based, lime-based, or earth-based matrices.

This paper aims to apply the knowledge generated through the study of the TRM in recent years to propose a reinforcing system for 3D-printed earth-based samples. By reinforcing earth-based materials with textile materials, these materials can be utilised more extensively in construction applications. This reinforcement process holds the potential to contribute significantly to the development and broader adoption of earth-based materials.

In this study, 3D printable earth-based mixtures, comprising entirely natural materials, were reinforced using Jute Fabric Textile, which is also 100% natural. The flexural and compressive strength results were analysed, and the implications and advantages of the reinforcement process were interpreted.

2. Materials and method

In this study, all materials used are natural, including raw earth (RE) (silt-containing soil), quarry wash mud (QWM) (clay-containing), and sea sand (SS) with a maximum grain diameter of 1 mm and a density of 2.06 g/cm^3. These components were combined without any binder or chemical admixture to create a 3D printable natural material using just the earth and water mix.

Tested raw earth consists of fine soil with a PSD showing 30% particles finer than 0.063 mm sieves. The quarry wash mud (clay-containing) contains siliceous mud (SM) and kaolin clayey mud (CM). The mud has a specific gravity of 2.65 and a specific surface area of 10 m2/g (data provided by the supplier). Its Plasticity Index (PI) is about 29, with a liquid limit of 63% and a plastic limit of 34%. The largest clay grain size is approximately 10 μm, and the mean kaolin grain size is about 4 μm. Finally, the 100% natural and biodegradable Jute fabric with a mesh size of 4 mm was used as a textile material.

The earth-based mixture was tried to be prepared to meet the rheological requirements so that it could be extruded on a 3D printer. After many preliminary tests based on trial and error, it was settled on the following proportions: 16% QWM, 40% SS, 44% RE and 21% water. QWM provided cohesion in the fresh mix and reduced internal and wall friction inside the extruder. The binding properties of clay minerals were activated by water and movement.

To measure the thixotropic behaviour (Shear Strength / Yield Stress) of earth-based mixtures, the Fall cone test, according to the European standard EN ISO 17892–6 (CEN, 2017), was applied [13] (see Fig. 1b). This test measures the penetration depth of a cone under an imposed load. From a rheological perspective, the contact between the cone's surface and the mortar will increase as it penetrates further. Thus, the resistance forces caused by shear stress will continue to increase to reach an equilibrium point with the applied mass. The cone was positioned so that its tip touched the surface of the mixture. The cone was then released for about 5 s to allow sufficient time to penetrate the material, and the penetration depth was recorded. The corresponding yield stress was calculated using this depth according to Equation (1)[14];

$$\tau = \frac{F cos\theta^2}{\pi h^2 tan\theta} \quad (1)$$

where τ is the yield stress (Pa); F is the force generated by the mass of the cone (N) (80 g = 0.78 N); θ is the angle of the cone used (30°), and h is the penetration depth (20 mm).

After preliminary experiments with the earth-based mixture, it was determined that a penetration depth of approximately 20 mm provided the desired rheological properties for 3D printing. These mixtures with a penetration depth of about 20 mm showed excellent printability. According to Eq (1), the yield stress of the earth-based mixture was calculated as 806.31 Pa for a penetration depth of 20 mm.

Five beam specimens, as shown in Fig. 2, with dimensions of 110 mm × 110 mm × 350 mm and a height of each layer of about 15 mm, totalling six layers, were produced using a WASP 3DMT 3D printer at a nozzle velocity of 2 cm/s. The specimen without any reinforcement is denoted by the letters EN (Non-strengthened Earth-Based). Jute textile was applied to the 3D printed specimens in a spiral shape and cut layer by layer to investigate whether the form of the application was important. The spirally applied samples are labelled with the letter S, while the cut samples are labelled with H (horizontal). In addition, samples were produced with one Jute textile in each 3D layer and one Jute textile in two 3D layers to investigate the effect of the number of layers. In this case, the sample names were as follows:

EN (Earth-based unreinforced): A sample where no reinforcement is applied, directly printed with earth-based mortar.

E1H (Every layer horizontally reinforced): Jute fabric is applied horizontally between each layer. The textile layers are independent and do not continue spirally to the upper layers. Each reinforcement is independent of the others.

E1S (Every layer spirally reinforced): Jute fabric is applied spirally between each layer, from the bottom to the top, creating a continuous spiral reinforcement.

E2H (Every two-layer horizontal reinforced): Jute fabric material is placed horizontally between every two layers.

E2S (Every two-layer spirally reinforced): Jute fabric is applied spirally between every two layers, from the bottom to the top, creating a continuous spiral reinforcement.

Unlike cement-based materials that cure through chemical hydration, earth-based materials harden through air drying. After being

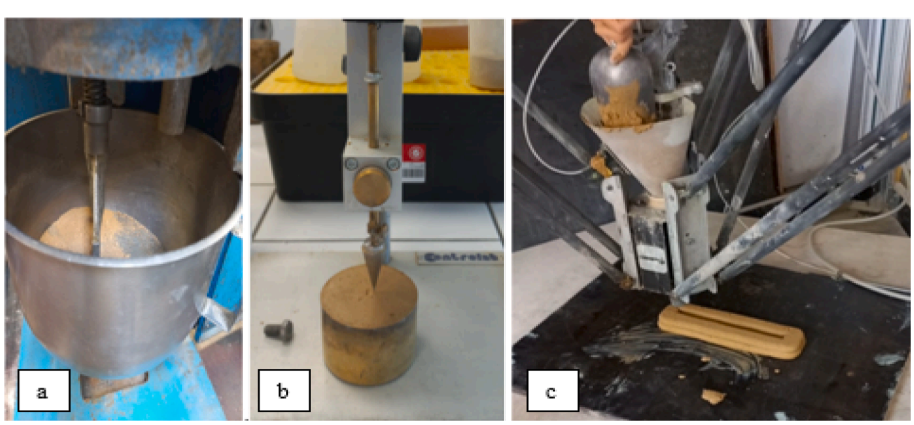

Fig. 1. A) mixing of earth-based materials, b) fall cone test, c) 3d printing of samples.

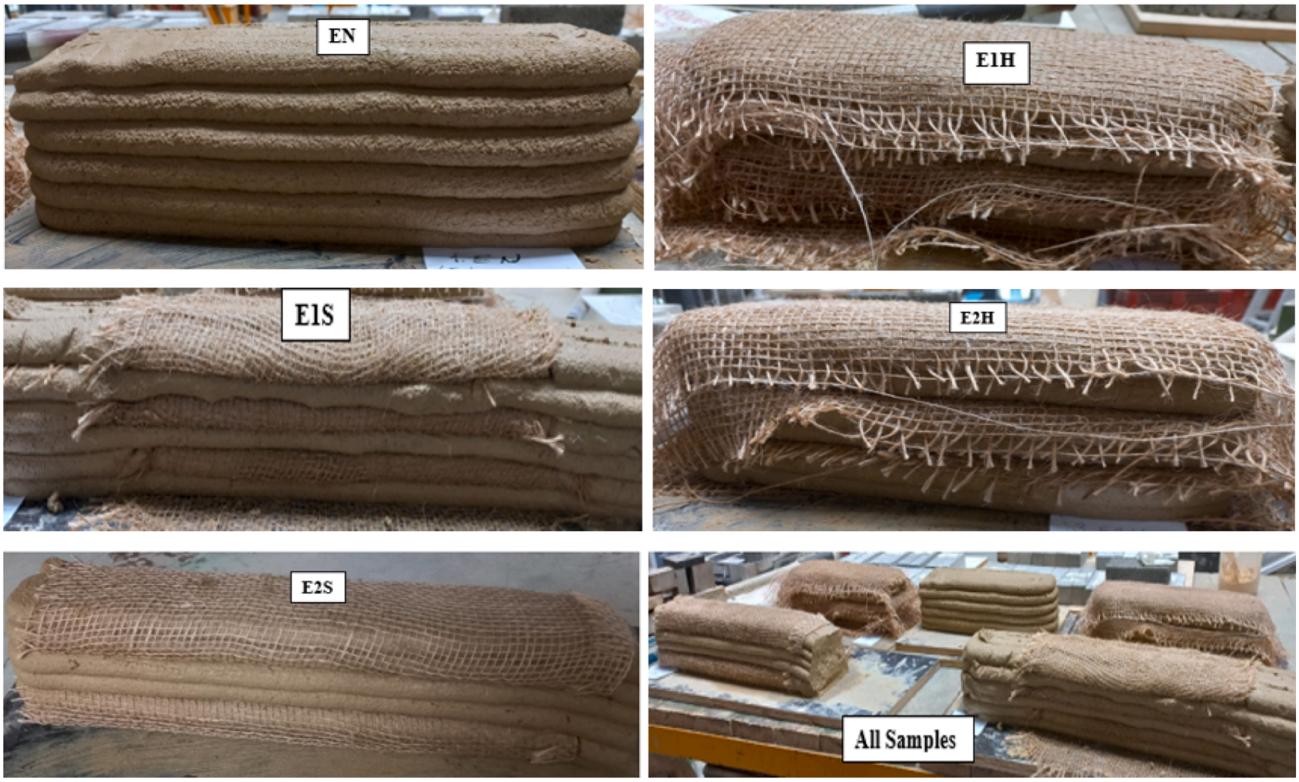

Fig. 2. 3D printed earth-based samples with jute fabric reinforced.

produced by 3D printing, the samples were initially kept in a laboratory environment at approximately 20 °C and 60% humidity for one day. Subsequently, they were placed in an oven at 60 °C for 14 days until they reached a constant weight. The graph depicting the time taken for the samples to reach constant weight is presented in Fig. 3. The wholly dried specimens were then subjected to a three-point flexural strength test. After this test, the obtained parts were cut using a cutting machine and subjected to compressive testing.

Compressive strength measurements were performed on 110 mm high 70 × 70 mm^2 cross-section specimens using a 50 kN loading frame (constant displacement rate of 1 mm/min). Deformation measurements were taken at the crosshead of the testing machine. Views of the experiment phase are given in Fig. 4.

3. Results and discussion

The flexural strengths of all groups are given in Fig. 5. The curves are plotted as force (N)-displacement (mm) to show the flexural behaviour.

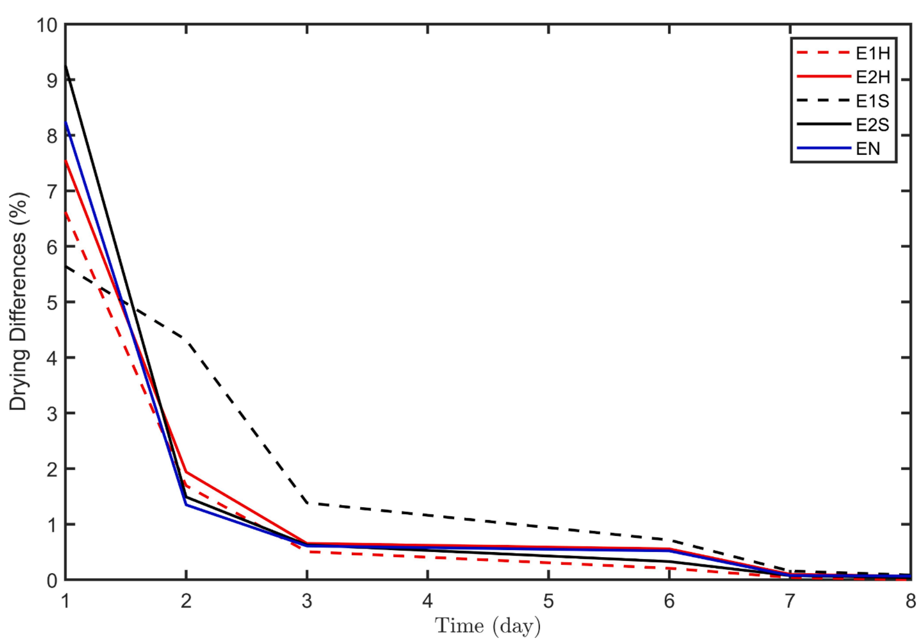

Fig. 3. The weight stabilisation of 3D printed earth-based samples.

Fig. 4. Flexural and compressive strength test of 3D printed earth-based samples.

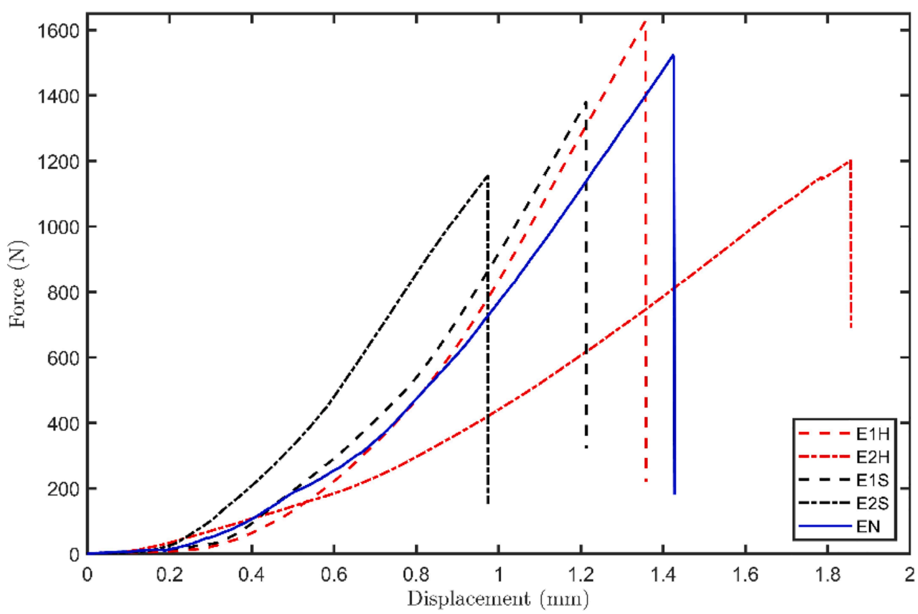

Fig. 5. Flexural strength test results.

The flexural strengths of EN (unreinforced) and four jute fabric reinforced specimens E1H, E2H, E1S and E2S produced by 3D printing are 0.48, 0.51, 0.38, 0.44, and 0.36 MPa, respectively.

The flexural strengths of all reinforced samples, except for E1H, which exhibited the highest flexural strength, were lower than the reference sample. The E1H sample showed an increase of 6.3% in flexural strength compared to the reference sample, while the E2H, E1S, and E2S samples demonstrated decreases of 20.8%, 8.3%, and 25%, respectively. Specimens with reinforcement applied in each layer exhibited higher flexural strength than other reinforced specimens. However, continuous application of spiral-shaped textiles negatively affected both strength and ductility, likely due to the weakening of the bond, as continuous application of reinforcement prevents the reinforcement and matrix from working as a whole. Moreover, using more reinforcement material in the H group specimens, where the reinforcement was applied by cutting, improved the ability of the layers to work together, enhancing rigidity and strength while limiting ductile behaviour. As a result, the E2H sample contained less reinforcing material, allowing the earth to deform more effectively, while the difference in the application of E1S and E2S samples showed higher deformation capability.

The compressive strength graph in Fig. 6 indicates that the specimens reinforced with jute fabric exhibited significantly higher deformation capability than the unreinforced specimen. Furthermore, the samples with reinforcement in each layer showed significantly higher strength and energy absorption capability, while the change in the strength of the specimens reinforced every two layers was negligible. Moreover, the behaviour of the reinforced specimens up to the peak load demonstrated high ductility, especially in specimens where each layer was reinforced. On the other hand, specimens with spiral or discrete reinforcement showed similar behaviour to each other. The highest compressive strength, about 1.15 MPa, was observed in specimen E1S. This strength value, obtained with purely earth-based materials without any binders or chemical additives, is satisfactory.

The results of the flexural and compressive strength tests are detailed in Table 1, showcasing the percentage differences from the reference sample. Negative values indicate a decrease in strength, while positive values signify an increase.

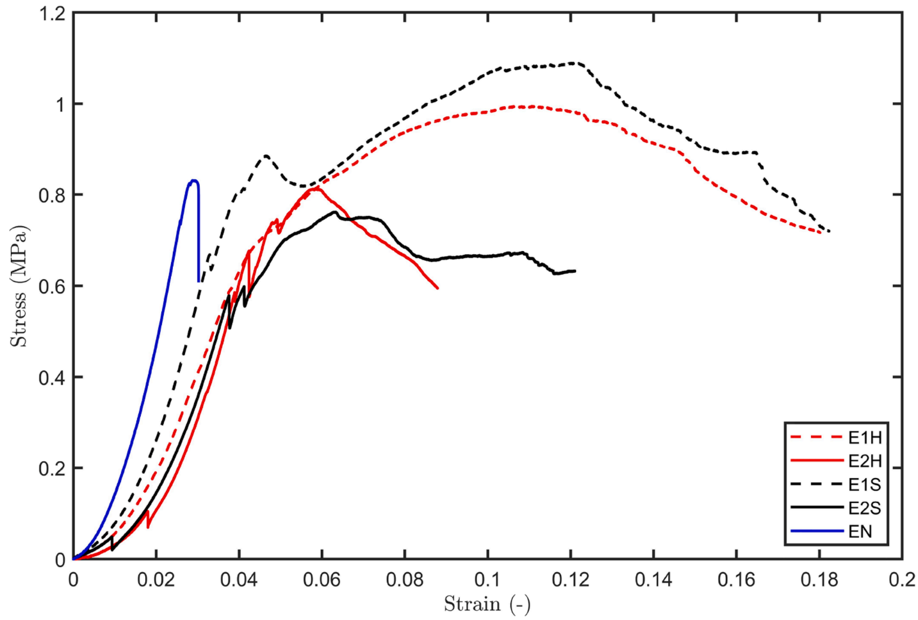

Fig. 6. Compressive strengths of 3D printed earth-based with and without jute fabric.

Table 1
Mechanical test results of 3D printed earth-based samples.

Sample Name	Flexural Strength (MPa)	Change compared to the reference sample (%)	Compressive Strength (MPa)	Change compared to the reference sample (%)
EN	0.48	-	0.84	-
E1H	0.51	6.3	0.99	18.38
E2H	0.38	−20.8	0.81	−3.51
E1S	0.44	−8.3	1.09	22.85
E2S	0.36	−25	0.76	−10.34

4. Conclusion

This study aims to promote using earth-based materials in the construction industry by investigating their 3D printability properties. Additionally, the study addresses the issue of reinforcement, a crucial challenge in 3D printing, by introducing textile fabrics as a new reinforcement method for 3D printed constructions. Textile reinforcement using 100% natural jute textile was implemented to strengthen the interface between the layers, resulting in a reduction in the mechanical properties of the 3D printable mixture composed of earth-based materials. Two different procedures were compared: continuous and discrete application of reinforcement.

The findings indicate that discontinuous application of reinforcement yields better results in bending behaviour, while both continuous and discontinuous methods exhibit similar reactions in compressive behaviour. The strength development was observed when reinforcement was applied by cutting and placing it between each layer, while a more ductile behaviour was achieved when reinforcement was applied in every two layers. In the specimens where a textile was applied in every two layers, although the difference in compressive strength is negligible, the ductility showed a considerable increase (approximately 500%). In the case of textile application in each layer, an increase of 25% in compressive strength and almost 1000% in ductility was obtained.

The results of this study highlight the promising potential of reinforcement application in significantly improving both ductility and strength. However, achieving the desired interlayer bond strength with textile reinforcement requires using the correct method and amount. Further research should focus on different processes to ensure adequate bonding of the textile reinforcement with the layers.

For the future phases of the study, it is recommended to enhance the strength of the 100% natural earth-based mixture by stabilising it with different binders. Moreover, implementing various measures to ensure better adherence to the textile reinforcement material is essential. The method recommended and demonstrated for its potential through experimental studies in this paper can also be applied to enhance the bonding and reinforcement problem of 3D printable materials, including lime, cement, geopolymer, etc., by incorporating high-strength textile materials. It is also important to investigate suitable methods in which the textile reinforcement can be included in the automation of the 3D printing process in order to pave the way for required further studies.

CRediT authorship contribution statement

Yeşim Tarhan: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Arnaud Perrot:** Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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