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Exploiting auxetic confinement for enhancing structural performance of earth-based construction

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Abstract

The construction and architecture industries have witnessed a growing interest in utilizing earth materials, driven by the urgent need for carbon-neutral building practices. Despite the low environmental footprint and high energy efficiency of earth-based constructions, a notable challenge persists due to their inherent weakness in strength and durability compared to concrete and steel. This shortcoming necessitates innovative approaches to bolster the structural performance of earth-based constructions while maintaining their ecological benefits. Earth confinement emerges as an effective strategy to enhance the compressive strength of earth structures, owing to the contribution of lateral confining pressure from the outer reinforcement. Auxetic materials, known for their counterintuitive behavior of becoming narrower when compressed, can introduce additional lateral confining pressure, thus offering a novel approach to earth confinement. This research explores innovative applications of auxetic materials in earth confinement. 3D printing is employed to fabricate auxetic tubes using flexible tough resin. Compression tests are carried out on the unstabilized rammed earth samples confined by auxetic tubes. In addition, the strengths of earth samples confined by traditional continuous cylinders and the proposed auxetic tubes are compared. The research outcomes present a novel approach to earth confinement, opening new avenues for auxetic material application in the construction industry. The findings also highlight the feasibility of removing cement as earth stabilization, thereby minimizing carbon footprints for construction practices.

Keywords: earth confinement, auxetic material, construction, 3D printing, sustainability.

1. Introduction

In the quest for sustainable construction practices, the architecture and construction industries are increasingly turning towards materials that minimize environmental impact without compromising structural integrity [1]. This movement is propelled by the urgent need for carbon-neutral building practices, amidst growing concerns over climate change and environmental degradation. Among the plethora of sustainable materials, earth has emerged as a prominent candidate [2].

The use of earth materials in construction is not new; it spans thousands of years, adapting to various cultures and climates around the world [3]. However, the modern resurgence of interest in earth materials is largely driven by sustainability concerns. Earth materials, primarily in the form of adobe, rammed earth, and cob, offer significant environmental advantages over conventional construction materials such as concrete and steel. These include lower energy consumption in production, reduced greenhouse gas emissions, and the use of locally sourced, abundant materials [4]. Despite these benefits, the mechanical properties of earth materials, particularly their strength and durability, lag behind those of more traditional construction materials, limiting their use in mainstream construction.

In response, researchers and practitioners seek innovative strategies to enhance the structural performance of earth-based constructions while preserving their ecological benefits. One such strategy is earth confinement, which leverages lateral confining pressure to bolster compressive strength [5]. Traditional earth confinement methods have utilized continuous encasements. While effective in increasing compressive strength, the continuous confinements often result in low material efficiency.

Auxetic materials exhibit the counterintuitive property of lateral contraction when compressed, characterized by a negative Poisson's ratio. This unique behavior has sparked interest in various fields, including medical devices, protective gear, and mechanical components [6], but their application in construction remains relatively unexplored. The potential of auxetic materials to provide additional lateral confining pressure [7] presents a novel approach to earth confinement, which could further improve the strength of the confined earth with the same amount of material usage.

This research investigates the integration of auxetic materials into earth confinement through experimental testing. To compare their efficacy, both auxetic cylinders and conventional continuous cylinders are 3D printed. These cylinders are then utilized to provide lateral confinement to rammed earth cylinder samples. Subsequently, uniaxial compression tests are conducted to evaluate the compressive strength of the produced samples.

2. Methodology

The methodology encompasses the design and fabrication of auxetic structures using 3D printing technology, the preparation of earth samples, and compression tests to evaluate the effectiveness of auxetic confinement compared to traditional counterparts. The following sections detail the materials, fabrication processes, and testing protocols employed in this study.

2.1. Material selection

In this project, unstabilized soil mixture is selected which consists of only soil and water. The soils are sourced locally in Victoria Australia to minimize environmental impact. Since the mechanical properties of earth material are sensitive to soil particle size and moisture content, desiccation and sieving are implemented to ensure the consistency of soil mixture for all samples. The raw soils are stored in an oven for 24 hours at 100°C to get rid of moisture content. They are then sieved into three size categories small: 0–2.36 mm, medium: 2.36–13.60 mm, and large: 13.60–20.00 mm. After sieving, soils in different size categories are mixed with equal portions by weight, and are added with 10% water by weight.

To fabricate the molds for confinement, flexible material is required to allow deformation for facilitating auxetic behavior. Anycubic UV Tough Resin is chosen due to its satisfying mechanical properties, including high flexibility and strength, which are essential for the effective confinement of earth materials. The major mechanical properties of the resin provided by the supplier are presented in Table 1. An Anycubic Photon M3 Max SLA 3D printer is used with the selected resin. The choice of SLA 3D printing ensures the production of auxetic structures with precise geometries and consistent material properties, essential for reliable testing and analysis. For large-scale construction, CNC milling with steel materials can be used to replace resin, thereby enhancing structural strength and reducing environmental impact.

Table 1: Material properties of the Anycubic UV Tough Resin [provided by [8]]

Hardness	76 Shore D
Tensile strength	35-45 MPa
Elongation at break	30–50%
Tensile modulus of elasticity	800–1200 MPa
Flexural strength	50–60 MPa
Flexural modulus	900–1200 MPa

2.2. Fabrication process

To achieve the negative Poisson's ratio, a classical auxetic pattern is utilized in the design of the molds, as illustrated in Figure 1. All molds feature an inner diameter of 100 mm and a height of 200 mm. Three different thicknesses of 3, 6, and 9 mm are implemented respectively to assess the impact of thickness on auxetic behavior. To ensure a fair comparison, the thicknesses of the continuous counterparts are calculated and adjusted so that the material usage remains consistent across both auxetic and non-auxetic molds. This approach allows for a thorough evaluation of the effectiveness of auxetic patterns in enhancing the structural performance of confined earth samples.

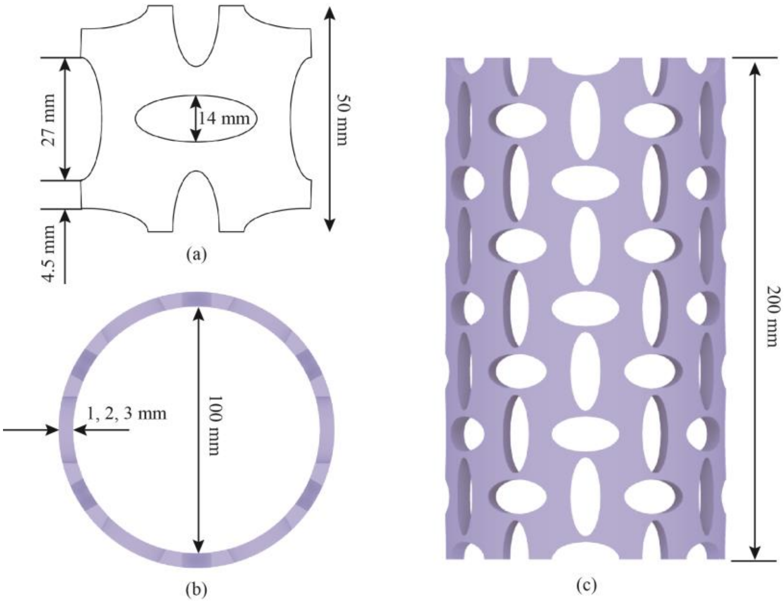


Figure 1: Geometry settings of the auxetic pattern.

The resulting 3D-printed molds for confinement are presented in Figure 2 (a). To facilitate the rammed earth process and prevent scattering of soil particles, a polyethylene thin film is attached to the inner wall of auxetic molds. For variable control purposes, the polyethylene film is also attached to the continuous mold. The confinement molds are then placed between two steel plates to secure the position and prevent movement during the ramming process (see Figure 2(b)), with the top plate having an opening hole for adding soil and allowing ramming.

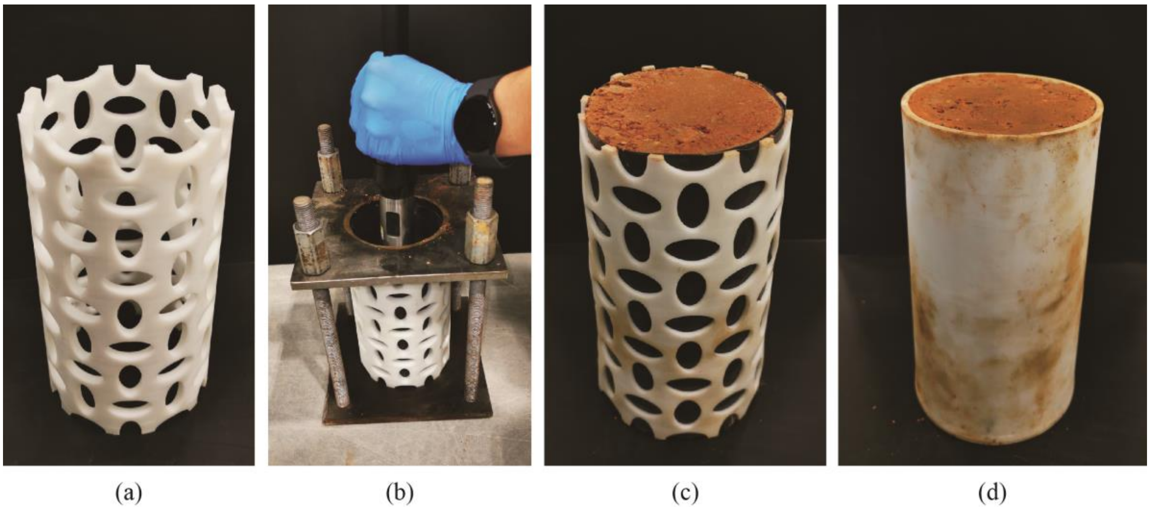


Figure 2: Sample fabrication: (a) SLA 3D printed flexible mold, (b) rammed earth process within the 3D printed mold, (c) final earth sample confined by auxetic mold, and (d) final earth sample confined by conventional continuous mold.

A KAWASAKI KPT-1 Sand Rammer is utilized to implement the ramming processing. To ensure sufficient compaction, the ramming process is strategically segmented into five layers for producing all samples. Following the compaction, a rubber hammer is employed to even out and level the top surface of each sample, ensuring uniformity. The completed samples confined by an auxetic mold and a continuous mold can be seen in Figure 2(c) and (d).

Subsequently, to allow for proper curing, the samples are stored under controlled indoor conditions, maintaining an average temperature of 20 °C and a relative humidity of 50%. Since the earth core is encased in polyethylene film and surrounded by the 3D-printed molds, the samples are positioned atop a base with steel mesh. This setup is crucial for promoting air circulation, thus enhancing the curing process by allowing moisture to escape effectively from beneath the samples. This curing process extends over a period of 28 days, during which the samples achieve their full strength and durability.

2.3. Unconfined compression test

Following a 28-day curing period, the samples are subjected to compression tests utilizing a TF-CTM5MN TruForce Static Hydraulic Testing Machine, as illustrated in Figure 3. The tests are conducted with a consistent load rate of 500 N/s maintained throughout the testing process. The compressions terminate at a strain level of 50% for each sample. The primary focus of these tests is to document the maximum compressive strength and observe the deformation patterns of each sample. The effectiveness of auxetic confinement is assessed by comparing these parameters across the different sample types and thicknesses.


(a) (b)

Figure 3: Compression test setup showing the earth core confined by (a) auxetic mold, and (b) continuous mold position in the center of the testing machine.

3. Results

Figure 4 displays the maximum compressive strengths observed for the earth samples confined within different molds of varying thicknesses. It is evident from the results that as the thickness of the mold increases, the maximum compressive strength of the samples also increases. A comparative analysis between samples confined by auxetic molds and those by conventional continuous molds underlines the strength enhancement afforded by the auxetic designs, given the same material usage.

Notably, the sample confined with a 3 mm thick auxetic mold exhibited a maximum compressive strength that is 2.3% higher than its continuous mold counterpart. For the sample confined by a 6 mm thick auxetic mold, the increase in maximum compressive strength is markedly higher, at 28.5% above the continuous mold sample. Meanwhile, the sample with a 9 mm thick auxetic mold shows a 6.4% increase in strength compared to the continuous mold. Clearly, the strength enhancement observed with the 6 mm thick auxetic mold is noteworthy, in contrast to the minimal improvements seen in the other two thickness groups. This phenomenon is attributed to the fact that a 3 mm mold thickness may be too small to provide ample lateral confinement strength, whereas a 9 mm thickness potentially restricts the lateral deformation necessary for auxetic behavior to effectively enhance strength. In contrast, the 6 mm thickness mold achieves an optimal balance, being flexible enough to allow for auxetic deformation while also providing adequate lateral confinement strength. Additionally, it is notable that the confined samples with 9 mm wall thickness—comprising solely of soil and water—achieve a compression strength comparable to that of unconfined, cement-stabilized rammed earth, which has an average strength of 6.36 MPa with a 10% addition of cement [9].

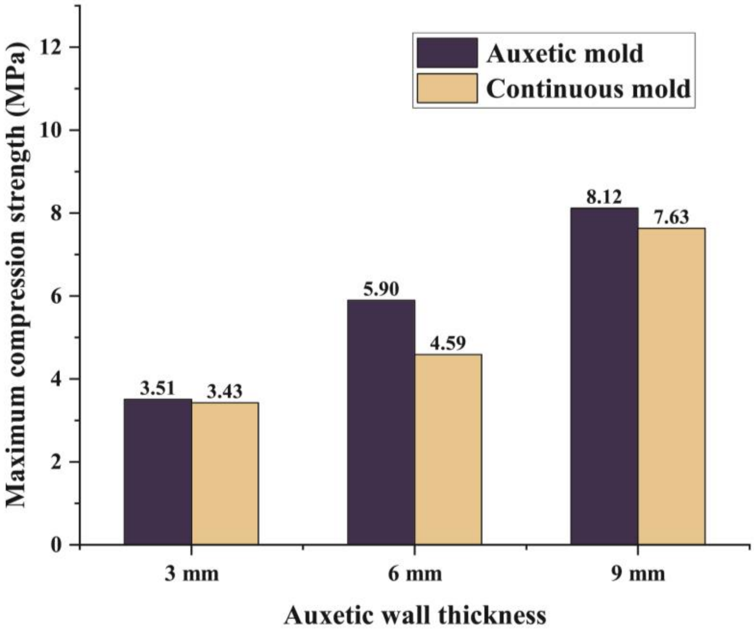
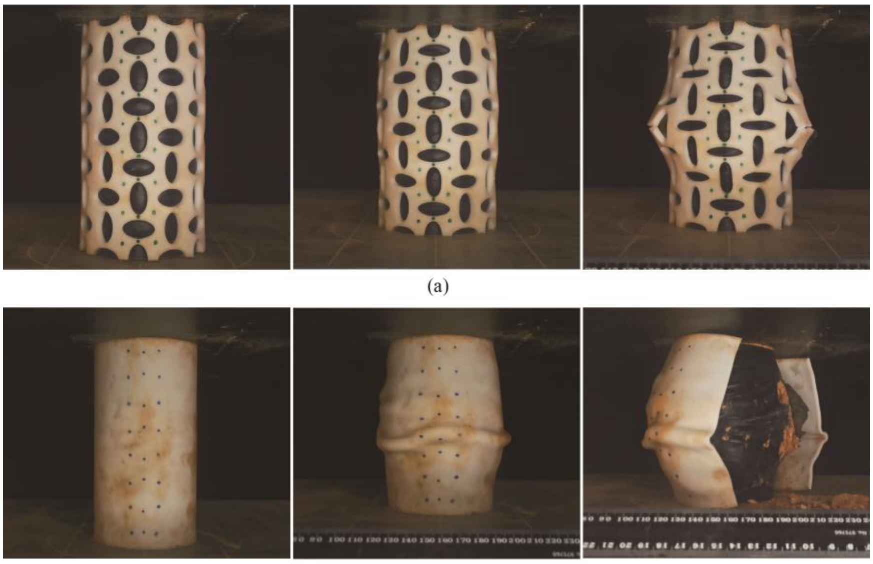


Figure 4: Maximum compressive strengths of the tested samples with different confinement and thickness settings.

The auxetic mold confers additional benefits, including enhanced profile maintenance of the cylinder and improved control over failure modes. Figure 5 illustrates the compression behavior of earth samples confined by the 6 mm thick auxetic mold versus those confined by a conventional continuous mold. The figure is organized into three columns for each sample type: the initial stage of compression is shown on the left, significant deformation in the middle, and the failure stage on the right.

In the significant deformation stage, as depicted in the middle column of Figure 5(a), it is evident that the sample confined by the auxetic mold retains the cylindrical shape effectively, exhibiting only minor expansion. Conversely, the sample confined by the continuous mold, as shown in the middle of Figure 5(b), undergoes considerable distortion and expansion, indicating less effective confinement.

Furthermore, the comparison of the failure modes between the two types of confinement, illustrated in the right columns of Figure 5, reveals distinct differences. The sample confined by the auxetic mold demonstrates a more gradual failure progression characterized by local buckling of the mold. In contrast, the sample with the conventional continuous mold tends to fail suddenly, resulting in a burst that creates a continuous fracture line. This abrupt failure mode presents significant safety concerns for building construction, highlighting the superiority of auxetic molds in mitigating such risks.



(a)

(b)

Figure 5: Deformation patterns and failure mode of earth samples confined by: (a) auxetic mold, and (b) continuous mold.

4. Conclusion

This study explores the innovative application of auxetic materials in the confinement of earth-based construction materials, aimed at enhancing their structural performance while adhering to sustainable construction practices. Through physical prototyping and subsequent compression testing, this study underscores the superior performance of auxetic-confined samples over their traditional continuous mold counterparts across various metrics. Notably, the auxetic tubes, particularly those of 6 mm thickness, demonstrated a remarkable ability to increase the maximum compressive strength of earth samples significantly, by up to 28.5%, compared to the continuous molds. This strength enhancement is attributed to the unique auxetic behavior, which allows for extra effective lateral confinement during compression. The results also reveal the potential of removing cement for earth stabilization with auxetic confinement, thus to minimize carbon footprints for earth constructions. Moreover, the auxetic molds exhibited additional advantages, including better maintenance of the cylindrical profile upon compression and a more controlled, gradual failure mode. These properties are crucial for the practical application of earth materials in construction, as they contribute to the overall stability and safety of the structure. The findings from this study present a compelling case for the adoption of auxetic materials in sustainable construction. By leveraging the unique properties of auxetic patterns for earth confinement, it is possible to significantly enhance the structural performance of earth-based constructions without compromising their environmental benefits.

Acknowledgements

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References

[1] G. L. F. Benachio, M. d. C. D. Freitas and S. F. Tavares, “Circular economy in the construction industry: A systematic literature review,” *Journal of Cleaner Production*, vol. 260, Article 121046, 2020.

[2] M. Gomaa, W. Jabi, V. Soebarto and Y. M. Xie, “Digital manufacturing for earth construction: A critical review,” *Journal of Cleaner Production*, vol. 338, Article 130630, 2022.

[3] H. Houben and H. Guillaud, *Earth Construction: A Comprehensive Guide*, Practical Action Publishing, 2008.

[4] L. Keefe, *Earth Building: Methods and Materials, Repair and Conservation*, Taylor & Francis, 2005.

[5] L. He, B. Khadka, X. Sun, M. Li and J. Jiang, “Compressive strength of rammed earth filled steel tubular stub columns,” *Case Studies in Construction Materials*, vol. 17, Article e01379, 2022.

[6] X. Ren, R. Das, P. Tran, T. D. Ngo and Y. M. Xie, “Auxetic metamaterials and structures: a review,” *Smart Materials and Structures*, vol. 27, Article 023001, 2018.

[7] C. Luo, X. Ren, D. Han, X. G. Zhang, R. Zhong, X. Y. Zhang and Y. M. Xie, “A novel concrete-filled auxetic tube composite structure: Design and compressive characteristic study,” *Engineering Structures*, vol. 268, Article 114759, 2022.

[8] Anycubic, “UV Tough Resin,” [Online]. Available: https://store.anycubic.com/products/uv-tough-resin. [Accessed March. 02, 2024].

[9] H. Anysz and P. Narloch, “Designing the composition of cement stabilized rammed earth using artificial neural networks,” *Materials*, vol. 12, Article 1396, 2019.