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Recyclability of Earth-Fiber Materials for 3D Printing

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Abstract

Advanced fabrication using additive manufacturing is predominantly focused on cementitious and petroleum-based materials, which have a high carbon footprint and low recyclability potential. As a result, development processes, which are heavily experimental for digital fabrication technologies, result in large quantities of spoil and waste. Novel bio- and geo-genic materials that are readily available, minimally processed, and non-toxic, may provide a critical solution to low-carbon, fully recyclable 3D printing futures. These materials may prove critical not only in the construction industry but also in educational mock-ups and research design and development. This paper presents the first comprehensive assessment of the viability of fully recyclable earth-fiber composites for 3D printing, developed at scale for pedagogical purposes in design. Using a micro-to-macro material design approach, the developed earth-fiber-bio composites were assessed for their structural behavior and recyclability potential. Once fully dried, the designed artifacts were rehydrated and utilized as a paste to create recycled 3D-printed specimens. A comparison of compressive strength and printability was performed for newly prepared and recycled earth-fiber materials. The selected composite, made with hemp fibers, clay soils, and biopolymer additives, was then used in a week-long hackathon with a 3D Potter Scara Elite large-scale printer to produce real-scale designs while instrumentalizing the circularity potential of the materials. As a final demonstration, the fabricated designs were showcased in an exhibition on the university campus grounds, after which they were reprocessed and reused for further fabrication.

Keywords: earthen materials, bio-based materials, recyclability, compressive strength, additive manufacturing, regenerative design

1. Introduction

Earthen building materials represent an established and essential resource for construction. In modern times, they offer a minimally processed, locally available, thermally efficient, low-carbon, non-toxic, and community-driven alternative to conventional building materials such as concrete [1]. To ease their adoption in contemporary applications, the utilization of advanced fabrication technologies, such as additive manufacturing, is helping the revamping of these materials and taking advantage of their environmental and technical performances [1], [2], [3] .

Previous examples of 3D printed earth construction are evident in experimental showcases, like the pavilions created by the Institute for Advanced Architecture of Catalonia (IAAC) [2], [4] and the MUD Frontier project undertaken by the initiative Emerging Objects [5].

Important developments of mix designs include increased fiber content [6], [7], [8] and biopolymer additives [9]. Various material ratios and additives, such as alginate were tested to address typical issues like enhancing the green strength workability of 3D printed earth materials [10]. Moreover, sand and natural fibers were proved to be effective solutions to reduce shrinkage, while increasing the ductility of earth mixtures [11], [12]. Drawing inspiration from traditional earth construction techniques, it has been

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demonstrated that augmenting natural fiber reinforcement can enhance both structural stability and water retention properties [13], [14], [15]. Nonetheless, the fiber content is usually contained at a 0.5 to 2 wt% of the total mass in order to maintain the extrudability of the paste [10], [11], [12], [16]. In this context, research work preceding this study has begun exploring methods to maximize the fiber content in 3D printable mixtures through the addition of biopolymers as rheology and viscosity modifiers [6], [7], [17]. However, even if earth materials have been proven to be fully recyclable admixtures for 3D printing when soil is the only constituent, [18], these prior fiber ratio increase efforts lack a comprehensive assessment of the structural strength affected by recyclability of earth components incorporating natural fibers and biopolymers.

In light of these gaps, this research focuses on examining the recyclability potential by comparing the compressive strength and linear shrinkage of large-scale 3D printed elements from newly developed mixtures vs. recycled ones. This investigation was carried out as part of a 5-days hackathon, which served as a case study to simulate a real construction site with limited resources and time constraints to develop the material and assess its printability. This hackathon aimed to provide future designers with an immersive, hands-on experience into the possible applications and digital fabrication of earth-based materials.

2. Materials and Methods

2.1. Materials and software

The materials utilized in this project were sourced from various regions of the United States. Newman Red Clay, manufactured in Laguna in California. Complementing this was a standard-graded Ottawa sand (Humboldt Mfg. Co, Illinois), sourced from Ottawa, Illinois. Hemp fibers were added to the mix design as reinforcement, precisely cut to 3mm length and sourced from Tennessee. To enhance the printability and green strength of the base paste material, sodium alginate sourced from Cape Crystal, New Jersey, alongside methylcellulose (Pure Original Ingredients, Utah), both serving as stabilizers and rheology-modifying agents [7], [10]. The Scara Elite v2 from 3D Potter, manufactured in Florida, USA) was chosen as a robotic arm that is usually utilized with the Mighty Small 50 pump (Imer Group, USA) facilitating precise control and efficient printing processes with adjustable flow rates and optimum aggregate size capabilities of up to 6 mm. The Scara printer were used with a 20 mm nozzle size. The geometrical variations developed during the hackathon have been designed in Rhinoceros 7 and the gcode generation script was developed in Grasshopper 3D-modeling engines (Rhinoceros 7, Robert McNeel & Associates).

2.2. Methods

The objective of this study was to concentrate all of the typical 3D printing research efforts from the printable mix design definition to the digital design fabrication all within a strict time limit of 5 days, coinciding with the duration of the hackathon event. The procedure, further detailed below, included the following five steps: i) defining a 3D printable mix design suitable for large-scale applications, ii) assessing compressive strength, iii) measuring linear shrinkage, iv) defining material recycling protocols, and v) evaluating the structural compressive strength and shrinkage of the 3D printed recycled material.

2.2.1. 3D printable mix design for large scale applications (extrudability from pump)

The objective of this phase was to define a highly fibrous paste that could be extruded from the material pump. Following the methodology proposed by Akemah and Ben-Alon [7], printable light fiber clay mixtures adapted to meet the printability requirements of the Scara Elite v2 robotic arm were defined, of which a selected mixture was further adapted for the use with the Scara large scale printer.

2.2.2. Compressive strength

Cubic samples of 50x50x50 mm were tested with an axial strain rate of 0.5 mm/min using an MTS Criterion Model 70 testing machine (Eden Prairie, MN). The unconfined compressive stress, σ_u, was taken as the maximum load obtained per unit area. For each recycling iteration, three samples were produced and analyzed and the compressive strengths of new and recycled samples were then compared.

2.2.3. Linear Shrinkage

The linear shrinkage test was conducted using a steel mold of size 305×25×25 mm. Samples were prepared by placing the mixture into the mold, then compacting, and smoothing the top surface. Subsequently, the samples were demolded after 3 days and let dry at a temperatures of 21°C for 6 days until a constant mass was achieved. The length of these samples was then measured to assess the impact of drying on linear shrinkage. A total of 6 samples were prepared and tested for each recycling iteration. The following Equation (1) was utilized to determine the linear shrinkage:

$$\text{Equation 1: } Linear\ Shrinkage = \left[1 - \frac{length\ of\ dried\ sample}{initial\ length\ of\ sample}\right]\ \%$$

2.2.4. Recyclability strategies

To define an appropriate recyclability strategy, it is fundamental to take into consideration the tendency of natural fibers and biopolymers to mold if left in contact with water for long periods of time. Three time frames, namely 12 h, 24 h and 36 h, were evaluated to assess the amount of time needed to achieve a new workable and fully hydrated paste for 3D printing while preventing mold growth from occurring. Moreover, a protocol to control the water content was also defined.

2.2.5. Hackathon demonstrator

As a conclusion, two teams of 6 students each participated in the 5-day hackathon to fabricate physical objects that could serve as demonstrators of the digital fabrication workflow while utilizing earth- and bio-based material for the Scara Elite robotic arm. In particular, material preparation strategies and printing parameters were defined.

3. Results and discussion

3.1 3D printable mix design for large scale applications

First, clay and sand were mixed in a proportion of 2:1 sand/clay according to the typical ratios utilized for cob materials [19]. Secondly, alginate and methylcellulose were added in a total of 2wt% to enhance material viscosity, rheology, and consequently, printability. Hemp fibers in a ratio of 2wt% were added to the mix as reinforcing additives. The quantity of water utilized was defined as 25wt% as suggested by Gomaa et al. [16]. In large scale 3D printing applications, the fiber content is usually limited to 0.5-2wt% due to the aggregate size limitation of pumps and the relation between nozzle size and maximal fiber length to avoid clogging [4], [5], [6], [7], [8], [9]. Considering that the aim was to maximize the fiber content in the printable paste, fibers and water were added in batches at a time until it was not possible to be extruded from the pump, which in this case corresponded to 4wt%. The final mix design with the maximized fiber content is presented in Table 1.

Table 1: Light Hemp Clay mix design ratios

	Clay	**Additives**		**Fiber**	**Water**	**Sand**	**Total**
	Newman Red Clay	*Sodium Alginate*	*Methyl Cellulose*	*Hemp Fiber 3mm Lenght*	*Tap Water*	*Ottawa Sand*	
Weight [g]	3,050	148	113	697	6,557	6,578	17,146
Weight [kg]	3.05	0.150	0.110	0.700	6.56	6.58	17.0
Density [kg/m^3]	1,600	1,000	500	150	1,000	1,600	/
Density [g/cm^3]	1.60	1.00	0.500	0.150	1.00	1.60	/
Volume [cm^3]	1,906	148	226	4,649	6,557	4,111	17,600

Ratio wt%	*18%*	*1%*	*1%*	*4%*	*38%*	*38%*	*100%*
Ratio vol%	*10.8%*	*0.8%*	*1.3%*	*26.4%*	*37.3%*	*23.4%*	*100%*

3.2 Recyclability strategy

Figure 1 summarizes the steps defined to assess the first recycling iteration (4.b instead of the typical material disposal in a linear economy, here demarcated as step 4.a), to evaluate the remaining structural capability of a recycled earthen paste containing natural fibers and biopolymers. After the first testing and printing campaign, the samples were dried in an oven at 105°C for 24 hours until the mass stabilized. The time frame of 24 h was shown to be the most successful for the water soaking period to making the recycled material achieve fully rehydrated paste. The quantity of water added followed the ratio here developed, namely 38 wt% of the dried mass, and then the paste was mixed for 1 hour until a smooth consistency was obtained and the possible clumps of fibers eliminated. Subsequently, samples for compressive strength and shrinkage were created to assess the material properties after the initial iteration of material recycling (see sections 3.3 and 3.4 for results). Additionally, extrudability and buildability properties were evaluated. However, during the extrusion of the recycled paste, discontinuous flow was observed, a characteristic that by definition suggest a not extrudable material, and clumps formed again while the material sat in the pump container. This outcome suggests that the recycled material requires re-stabilization with additives to restore the desired rheology modification and consistency enhancement and prevent aggregation. Moreover, it suggests that the interaction between the rehydrated biopolymers, fibers, and clay particles should be further analyzed on the micro-scale and fundamental material science front.

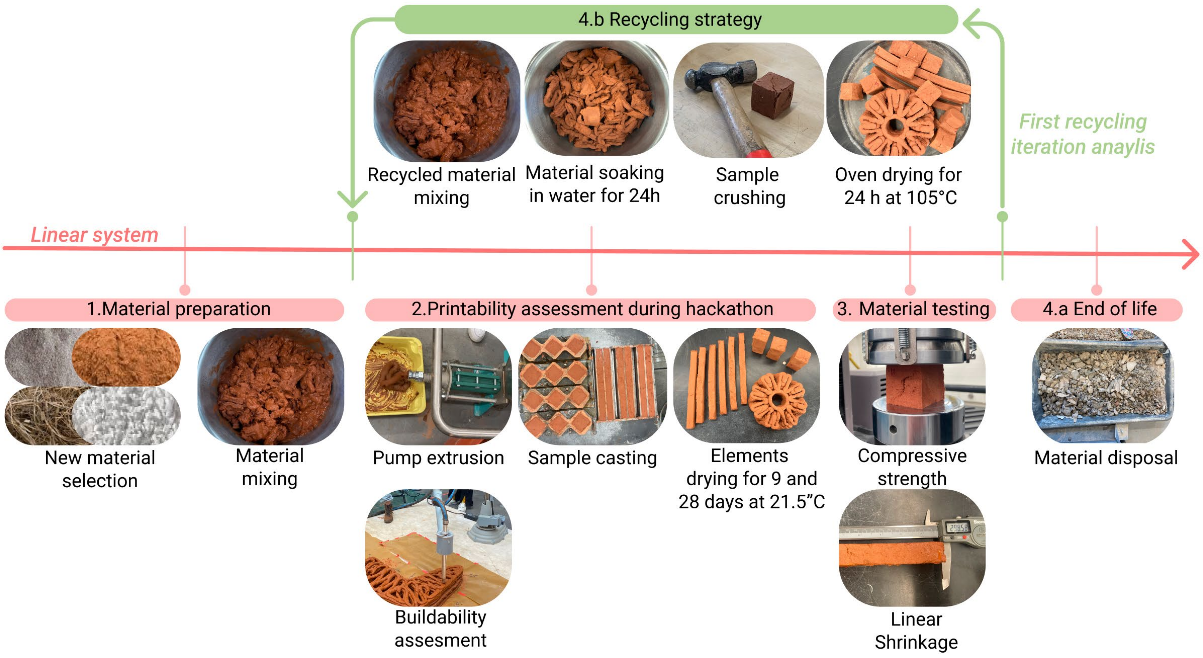

Figure 1: Recyclability strategy in a circular perspective for high fibrous earth-materials

3.3 Comparing the compressive strength among new and recycled materials.

Figure 2 summarizes the compressive strength results for the two examined sets of composites: new and recycled. The sample exhibited an average compressive strength of 1.70 MPa associated with the newly prepared earth mixtures (in red) after 9 days and 2.45 MPa after 28 days. The recycled mixtures (in green) are characterized by a compressive strength of 2.33 MPa after 9 days and 2.23 MPa after 28 days, however the error bars suggest that they are located in the same value ranges. This disparity between the new and the recycled results can be primarily attributed to the speed that the different material mixtures need to get the final strength. Furthermore, the final strengths of both mixtures are statistically comparable, indicating that the material does not undergo property degradation after the first recycling cycle.

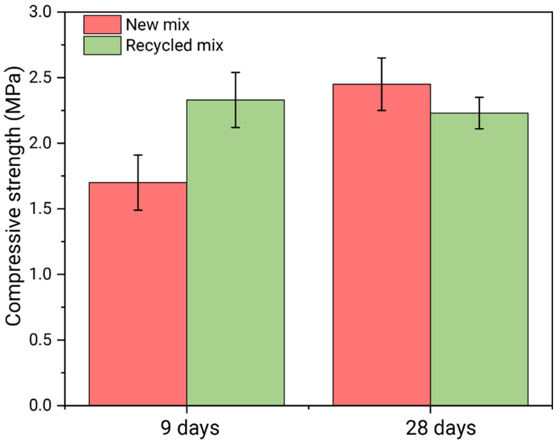

Figure 2: Compressive strength results of the developed new (red) and recycled (green) 3D printable earth-fiber composites with maximized fiber content. Error bars indicate the standard deviation.

3.4 Comparison of the linear shrinkage between new and recycled materials.

Figure 3 highlights that both new and recycled mix designs reached linear stability after 4 days. The new mixture is characterized by a higher variability of linear shrinkage ranging from 8 to 2%, whereas the recycled mixture reached a linear stability between 4 to 2% after the second day of drying. These findings align with the compressive strength results, indicating that the material also attains its final length more rapidly compared to the new mixture

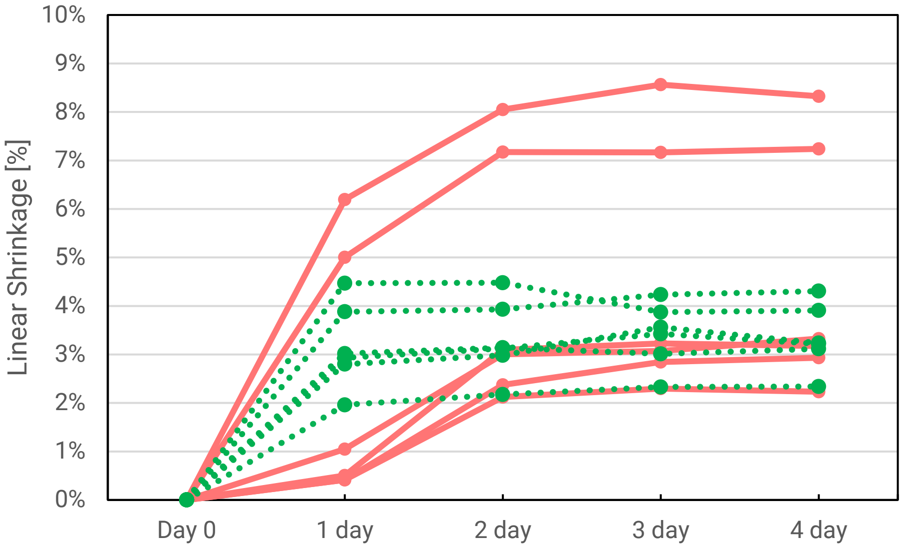

Figure 3: Linear Shrinkage of newly prepared mixtures (red) vs recycled (green).

3.5 Hackathon demonstrator

During the hackathon workshop, the main printing parameters were defined. The layer height was defined as 10 mm, i.e. half of the nozzle size, since it assured proper bonding between layers. A buildability of at least 5 consequential layers was observed, and a printing speed of 50mm/sec was set in the gcode file generator in Grasshopper to ensure sufficient flow of material through the pump. The pump extrusion was kept constant at 0.11 cubic meter per hour. A minimum of 17 kg of material was required to completely fill the pump container for each printing batch, and it was observed that the material needed a constant minimal vibration to assure a continued extruded line while printing. This vibration was maintained through a continuous, slight movement of a tamper, the extremity of which protruded from the pump grid (see first image on the left of Figure 5).

From a design perspective, two objects were created: a small column-table and a bench (Figure 5). To assure a good buildability and print the two objects simultaneously, it was decided to print 7-10 consecutive layers per geometry and then let the material set for 24 hours before resuming the printing session the day after. The number of consecutive layers was mainly dictated by the overhang incorporated in the column table design. A further analysis could provide a more geometrically stable element by increasing the overlapping portion of curves while defining the printing line path.

Figure 4: Hackathon printing session: From the left: tamper vibrating; table-column printing; bench printing; bench printing resuming after 24 h.

The final elements printed were assembled and finished with wooden elements and details, as depicted in Figure 6.

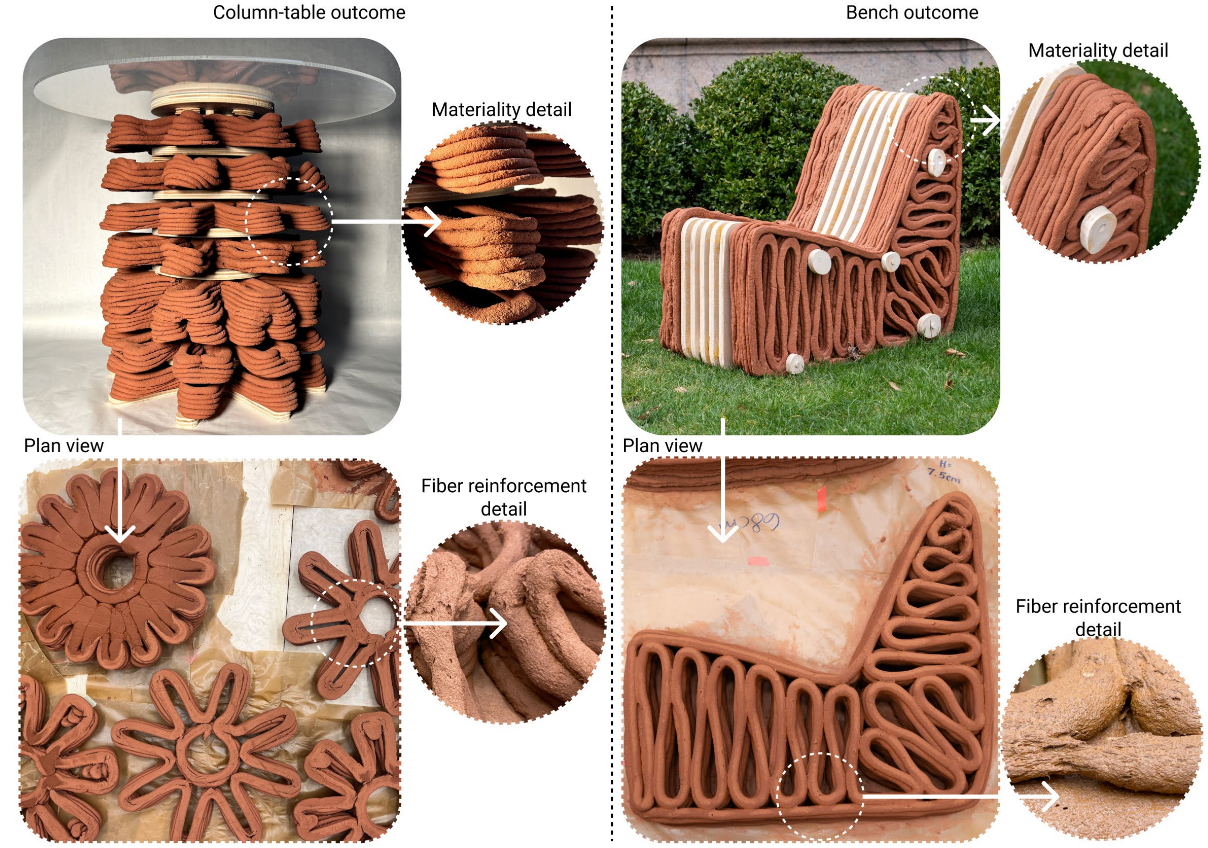

Figure 5: Final objects printed as a demonstrator of the methodology defined during the 5 days hackathon. Form the left: table-column with zoom of the material texture; bench with a zoom of the material texture.

4. Conclusion

3D printed earth-fiber is an emerging field that requires further investigation. Specifically, the recyclability potential of mix designs is crucial for the circularity and environmental features of earth-fiber materials in digital fabrication. To address this potential, this study investigates the structural performance of earth-hemp composites through a hackathon demonstrator of the materials. The findings of this study highlight the following conclusions:

- A mix design suitable to be printed in the Scara Elite v2 printer and Mighty Small 50 pump environment was defined as follows: clay 18 wt%, alginate and methylcellulose 2 wt%, hemp fiber 4 wt%, water 38 wt% and sand 38 wt%. In this mixture the fiber content was maximized to respect the pump aggregate dimensions. Moreover, the final water content is higher than other examples of 3D printed earth materials (usually around 25 wt%).
- The 24-hour period proved most successful for immersing the recycled material in water, resulting in a fully rehydrated paste.
- The recycled mixture exhibited some discontinuity and nozzle clogging while printing, suggesting that more additives should be reinserted.
- New mixtures are characterized by a compressive strength of 1.70 MPa after 9 days and 2.45 MPa after 28 days, and recycled mixtures achieving 2.33 MPa after 9 days and 2.23 MPa after 28 days, suggesting similar final strengths despite different speeds to reach the final strength.
- The new and recycled mix designs achieve linear stability after four days, with the new mixture exhibiting greater variability in linear shrinkage (8% to 2%) compared to the recycled mixture, which reaches stability (4% to 2%) by the second day of drying, consistent with the faster attainment of final length observed in the compressive strength results.
- The final element printed, namely the table-column and the bench, provided tangible representations of the innovative ideas generated during the hackathon.

Future research should focus on investigating the increase in compressive strength of recycled materials from a micro-analysis perspective. Additionally, conducting a more in-depth testing campaign to enhance the statistical significance of the results, and testing further cycles of recycled elements to assess their compressive strength behavior, is needed. Life-cycle analysis, focusing on comparing the newly printable mixture with the recycled one containing more additives, should also be conducted. Indeed, Carcassi et al. demonstrated that biopolymers account for 34–50% of the global warming potential (GWP) of earth and fiber-based mix design [6]. Therefore, a more in-depth analysis of two 3D printed wall assemblies using the newly and recycled mixtures can suggest the most viable future for such a 3D printed element.

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