Developing 3D-Printed Natural Fiber-Based Mixtures

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Abstract. Natural earth-fiber building assemblies such as light straw clay, hempcrete, and clay-plastered straw bales incorporate vegetable by-products that are mixed with geological binders, traditionally used as an insulative infill in building construction. As a geo- and bio-based insulative infill method composed mostly of fiber, heat transfer coefficients are lower than mass materials, making it a compatible assembly that meets energy code requirements. Furthermore, due to their permeability, these materials exhibit high hygric capacity, providing regulated indoor temperatures and relative humidity levels, thus showing a promising future for socially just and healthier built environments. Despite these advantages, the use of earth-fiber building materials in digital construction is still underdeveloped. In the past few years, 3D-printed earth has gained an increasing interest, however, high contents of fibers in earth mixtures have yet to be fully tested and characterized. This paper presents an experimental workflow to characterize fiber-earth composites for 3D printed assemblies, using natural soils infused with natural fibers. The paper begins with a literature review of a range of fibers: straw, hemp, kenaf, sisal, and banana leaves, as well as naturally occurring biopolymer additives. The experimental setup includes manual extrudability and buildability tests, to identify optimal mix designs that are then tested for their printability and buckling using clay 3D printers. As a final deliverable, first pass geometric studies showcase the lightweight and structural possibilities of each material. The significance of this research lies in the development of a methodology for identifying novel mix design for digital fabrication, by increasing carbon storing vegetable fiber content within digital earth, and by creating a range of natural 3D printed assembly types: from mass-insulation walls to paper-thin lightweight partition assemblage.

Keywords: Natural building materials · Earth- and Bio-based building materials · Light straw clay · 3D printing · Additive manufacturing

1 Introduction

Earth-based construction materials have been gaining interest in recent years due to their environmental impacts and affordability (Van Damme and Houben 2018). Earth-based construction (interchangeably termed as earthen materials, or generally addressed

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as "natural building") is a field of building materials and construction techniques that incorporate clay-rich soils as a base matter, infused with other geological products (such as sand, larger stone aggregate, and lime), and fibers (such as wheat straw, rice straw, and hemp). Earth-based construction has been used for thousands of years and is still prevalent in many parts of the world. Earth-based materials have been shown to exhibit significantly lower embodied energy and emissions as opposed to conventional materials such as concrete due to their minimal thermal and chemical processing (Ben-Alon et al. 2021). Further ways to increase the environmental opportunities of earthen construction is to increase fiber content within the mix design due to its carbon storage and lighter weight for transportation.

The use of fiber proposes advantages throughout production to disposal (cradle to grave). During the growth cycle of fibers, carbon dioxide is consumed through photosynthesis, removing it from the atmosphere (Walker et al. 2019). Furthermore, the cultivation of bast fiber crops requires fewer pesticides and fertilizers, thus reducing risks for acidification and eutrophication (Fernando et al. 2015). In building construction, the use of locally available fibers is ideal to reduce carbon emissions from transportation due to their low weight and packaging possibilities. Natural fibers also improve ductility (Miccoli et al. 2014) and thermal properties (Holzhueter and Itonaga 2017). During the operational phase, earth assemblies with high contents of natural fibers help reduce operational emissions by increasing thermal resistivity, coupled with the mass capacity (Rempel and Rempel 2016; Shang and Tariku 2021). Some examples of natural fibers that are commonly used in building construction are straw, hemp, flax, fique, banana, jute, sisal, animal hair and wool.

Despite these benefits, the use of earth-fiber assemblies remains a marginal field in sustainable construction due to a range of constraints, including the labor intensity of construction using these materials and their techno-mechanical-thermal properties that requires further characterization. The use of 3D printing can therefore introduce accuracy (due to the machine manufacturing) while reducing labor needs (Correa et al. 2015).

This paper presents a workflow for identifying earth-fiber mixtures suitable for 3D printed architectural applications. Illustrated in Fig. 1, this research proposes a methodology for developing earth-fiber mixtures for 3D printing of architectural artifacts, starting with a performance synthesis, to material selection, the tests include manual extrusion and buildability, microstructural electron scanning diagnosis, and digital printability using simple and complex geometries.

The proposed methodology is initiated with a literature review of a range of fibers, followed by a series of manual extrudability and buildability tests, and machine printability tests and processing parameters development. The final demonstration exhibits a successful implementation of earth-fiber materialities in 3D printed applications in small scale walls and paper-thin lightweight partition elements.

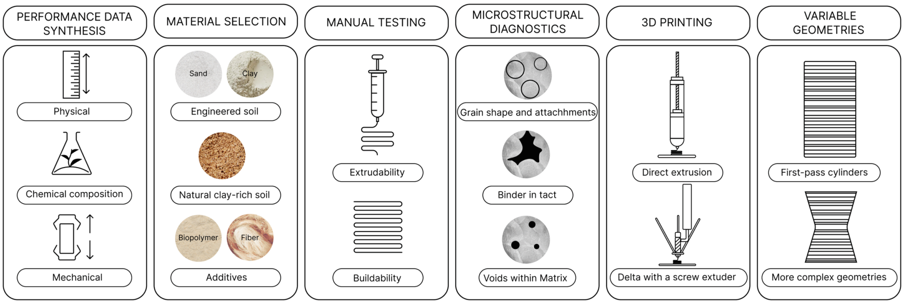

Fig. 1. The methodology developed as part of this research.

2 Background on Natural Fibers: From Traditional to Digital Construction

2.1 Traditional Earth-Fiber Assemblies

Earth-fiber materials use locally-adjusted mix designs in which clay-rich soils act as a natural binder, fibers act as the reinforcement (and, often, aggregate), with or without additives that may provide enhanced water resistivity (such as cow dung, cactus juice, flaxseed oil). Hempcrete, for instance, is an infill material made from hemp hurds (hemp shives) as a plant aggregate, and lime as a geological binder. As a construction material, hempcrete is a fire resistant, robust, and non-toxic building product, with a sequestering power of 135 $kgCO_{2e}/m^3$, primarily from the growth phase of the hemp plant and carbonation phase of the lime binder.

Fig. 2. Light straw clay workshop by The Year of Mud; Light straw clay monolithic wall construction, and; Manually constructed earth-fiber composites. Image sources: (Goodhew et al. 2021; Baker-Laporte, Laporte 2015).

Most relevant to this work, light straw clay (also known as light clay, straw clay, slip straw, rammed straw and leichtlehmbau), is an infill material that can be applied as a modular block or tamped within a structural frame. Light straw clay serves as an insulating material which can be mixed and packed into a variety of densities but is not load bearing. Shown in Fig. 2, the production process of light straw clay includes tamping the long stalks of fiber, mixed with clay slurry (very wet clay) which helps stiffens the mixture after compaction before drying. Besides acting as an insulation material, light straw clay is excellent for retrofit insulation due to its compatibility with structural wood frame (Ben-Alon 2020). Furthermore, light straw clay can easily be applied around windows, doors, and other openings. Light straw clay is also a healthy building material that serves as an alternative for individuals with sensitivity to mold and chemicals. Over their embodied phase, light straw clay assemblies were shown to reduce up to 70% in global climate change impacts, 55% in energy demand, 57% in air acidification, and 27% in air particle pollution as opposed to fiberglass insulated wood frame assembly (Ben-Alon et al. 2021). Over their use phase, light straw clay assemblies were shown to reduce energy consumption by 32–59% in hot desert climates, 29–55% in semi-arid climates, 46–73% in Mediterranean climates, 34–55% in temperate climates, and 27–50% in cold continental climates, as opposed to conventional building assemblies.

2.2 Reviewing Natural Fibers and Their Properties for Digital Construction

In order to identify natural fibers for 3D printed earth, a review study of the plant physical structure and composition was obtained, as shown in Fig. 3. Factors were chosen based on their influence on the final structure and 3D printing process.

Physical and Mechanical Properties. Fiber length was assumed to affect mixture production more than the dry state mechanical performance of the earthen composite. Previous studies have shown that fiber length has a minimal influence on the flexural strengths of earth materials such as cob (Pullen and Scholz 2011). However, the length of the fiber is important to the extrusion of mixtures through the nozzle during 3D printing. Similarly, smaller fiber diameter was assumed to reduce the risk of clogging within the extrusion flow mechanisms of the printers. Fiber with shorter natural lengths reduce the need for fiber processing prior to printing.

The flexural strengths of earth-fiber composites were shown to increase as a function of the fiber tensile strength (Pullen and Scholz 2011). Additionally, high absorption rates were shown to correlate with shrinkage and dimensional variation of the material caused by water evaporation (Laborel-Préneron et al. 2016).

Fiber Composition. There are three naturally occurring biopolymer components found in plants that affect the final material: cellulose, hemicellulose, and lignin. Cellulose is the primary element found in the cell wall of plants and is a polymer of carbohydrates ($C_6H_{10}O_5$). Cellulose is the most abundant organic polymer on Earth and can be found in all agricultural products and waste. It is a linear polymer of $\beta - (1 \rightarrow 4)$–linked D-glucose. Secondary to cellulose, hemicellulose (also known as polyose) is found in almost all plant cell walls, however, compared to cellulose structural make-up, hemicellulose molecules are branched shorter in length and show a tendency to crystallize (Smith et al. 2022). Lignin is the third most abundant reproducible natural resource and the only renewable aromatic polymer in nature (Suhas et al. 2007). Lignin is a cementing material found mostly in wood plant fibers, and is a polymerized hydrophobic amorphous substance, which is three-dimensional in structure and highly branched. Lignin is considered a waste product in certain industries (such as paper making), where it is removed by acid or alkali treatment, for its dissolution and fiber separation.

The complex structure and composition of lignin provide unique properties versus those of cellulose and hemicellulose. Lignin fills the cell walls between the cellulose, hemicellulose, and pectin molecules. As a structural component, lignin act as a support tissue of most plants (Saake and Lehnen 2007) thus greatly impacting the structural strength of plants. Lignin resists degradation, as opposed to cellulose and hemicellulose that are prone to biodegradation (Vane et al. 2003). Shrinking and swelling behavior of fibers is dictated by the movement mechanism of bound water, which escape from between cellulose and hemicellulose molecules (Reeb 2009). Lignin, however, reduces absorption rates, functioning as a water barrier, a critical characteristic for construction elements that are required to withstand weather forces and moisture. Despite this advantage, high lignin contents that decrease absorptive ability might also affect the fiber's ability to integrate within a mix design matrix, presumably because of fibers that absorb water may soften within the mix design.

From the fiber analysis, six fibers were deemed to be suitable for printability testing due to their chemical composition and source efficiency: straw, hemp, banana leaf, sisal, and kenaf, given their wide representation of physical and chemical composition properties.

3 Materials and Methods

The overall research procedure presented in this paper included three main steps, as shown in Fig. 1: (1) material selection following the literature review; (2) manual extrudability and buildability tests using a manual 2 mm syringe, and; (3) digital printability tests using two types of 3D clay printers.

The soil used in the research was of a dark grey-brown composition, sourced from a local quarry (Goshen, New York USA). This soil, characterized to its mineralogical content and particle size distribution, is presented in Bryson et al. (2021). Additionally, "engineered" soils were created by mixing bentonite and kaolinite clays with Ottawa sand. Throughout this study, naturally occurring biopolymers were used in quantities of 2% or less, due to their ability to modify the rheology of the material (Dourado et al. 2016). The main purpose of using biopolymers is to assist with the flowability (Malaeb et al. 2019). Additionally, biopolymers were shown to increase green strengths and the structural buildup of a 3D printed earth materials (Perrot et al. 2018). The biopolymers used included methyl cellulose, sodium alginate, chitosan, locust bean gum, guar gum, and xanthan gum.

3.1 Manual Extrudability and Buildability Tests

The extrudability and buildability were tested manually, using a 2 mm syringe. The hypothesis that underlies this test is that the 3D printed mixture is dependent on the cohesion between the binder (the clay-additive paste) and the plant fiber reinforcement. An optimal mix design would therefore have a high static yield stress which would result in shape retention and minimal buckling, thus supporting the weight of subsequent layers (Tay et al. 2019).

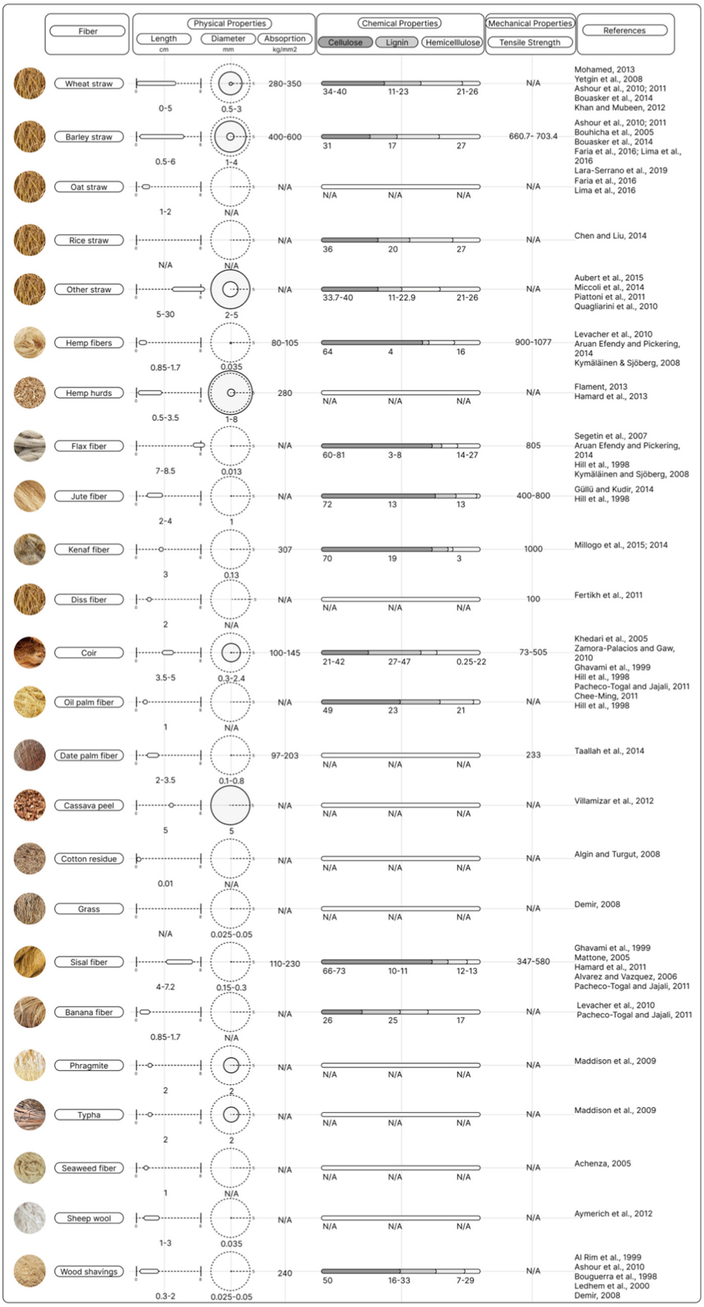

Fig. 3. Synthesized physical, compositional, and mechanical performance for natural fibers that have been previously used in earth-based construction. * N/A means not applicable.

The extrudability through the nozzle was evaluated qualitatively, assessing the flow and clogging or blockage of the mixture during the extrusion process. The buildability of the samples was assessed quantitatively by counting the number of vertically depositing 50 mm layers on top of one another. The buildability was also evaluated qualitatively by analyzing the adhesion between layers, the shape retention of the freshly extruded specimen, and the tendency of the built layers to collapse.

3.2 Microstructural Imaging

The microstructural imaging was conducted using a Zeiss Sigma VP scanning electron microscope (SEM), which combines electrostatic and magnetic fields in its optical performance. The aim of this step was to observe the extruded samples and correlate the extruded results with microstructural observations. The samples were observed to obtain insights about the arrangement of the clay and sand particles, and fibers, in relation to the extrusion directionality, the paste-aggregate interactions, and the quality and cohesion of the matrix at large.

3.3 Machine Printability Tests

Using the successful mixtures from the manual test, the printability was assessed using two types of 3D printers: a direct extruder clay printer (3D PotterBot 4 Pro), and a ceramic delta extruder with a screw system (Delta WASP 40100 Clay). Compared to the direct extruder printer, the delta extruder a printing system of three arms on a rail that operate vertically to move the print head, thus allowing higher geometrical precision. The nozzle radius used for the machine tests included 4, 5, 6, and 8 mm.

File Preparation. To conduct the machine 3D printing tests, a series of vase forms were created in Rhino3D modeling software, imported into a slicer software (3D version 5.0 by All3DP, and Cura version 4.3 by Ultimaker) to generate the G-code for printing. Nozzle sizes Simplify were also indicated within the slicer software to correlate to the material flow and speed. Additional parameters dictated within the slicer software included the primary layer height (the vertical distance between one layer to the next), which was set to half of the radius of the nozzle (2 mm to 4 mm, respectively), a value that was found to be optimal to ensure proper bonding between layers. Increased layer heights were also tested, showing a possible deposition of subsequent layers, though resulted in reduced grip between one layer to another. The preliminary geometry included basic cylindrical extrusions, followed by more complex forms that aimed to examine the geometrical variability and structural stability of the material.

4 Results

4.1 Manual Extrudability and Buildability Tests

The manual extrudability and buildability tests results showed, on an immediate observation, that only the straw and hemp fibers deemed to be soft enough to be extruded. Other fibers with high lignin content were too stiff to orient correctly in the direction of extrusion flow. Shredding the fibers using a Vitamix Blender (Vitamix 7500 machine, Vitamix Corp., Cleveland, OH, USA) was required in order to obtain the desired length, however, processing the fique, banana, and sisal fibers did not yield in shorter lengths but rather in lumps of aggregated fiber.

The printability tests shown in Table 1 and Table 2 indicate that the best extrudability and buildability are achieved for the alginate, cellulose, and locust bean gum additives. Mixtures with natural soils outperformed the engineered soils, assumingly due to the

Table 1. Manual extrudability and buildability tests for the soil-additive pastes

	Code	Composition	Soil (vol %)	Clay (vol %)	Sand (vol %)	Additive (vol%)	Water (vol%)	Extrudability*	Buildability **	Qualitative Assessment Notes
Engineered soil	NbS	Nanoclay Bentonite, Sand	-	29	29	-	42	3	4	Hardened sample is brittle
	BS	Bentonite, Sand	-	27	27	-	46	3	4	Hardened sample is brittle
	NkS	Nanoclay Kaolinite, Sand	-	38	38	-	24	3	1	Hardened sample is brittle. Extrudability is limited, fluids pushed down first.
	KS	Kaolinite, Sand	-	40	40	-	20	1	1	Hardened sample is brittle. Extrudability is limited, fluids pushed down first.
	BA	Bentonite, Sand, Sodium Alginate	-	13	50	1	35	3	2	Mixture is too dry to extrude but additional water would render the mixture unbuildable
	KA	Kaolinite, Sand, Sodium Alginate	-	15	60	2	23	1	0	Low water retention does not allow the mixture to be extrudable or buildable
	BGg	Bentonite, Sand, Guar Gum	-	12	46	1	41	4.5	3	Too wet for enhanced buildability results
	KGg	Kaolinite, Sand, Guar Gum	-	13	49	1	38	4.5	4	Too wet for enhanced buildability results – material quickly collapses
	BLbg	Bentonite, Sand, Locust Bean Gum	-	12	46	1	41	3.5	5	Result is buildable, however clogs in extrusion
	KLbg	Kaolinite, Sand, Locust Bean Gum	-	13	52	1	33	3.5	4	Result is buildable, but extrudability requires more water.
	BXg	Bentonite,Sand, Xanthan Gum	-	13	52	1	33	3.5	5	Result is buildable, material quickly stiffens
	KXg	Kaolinite,Sand, Xanthan Gum	-	14	56	1	29	4	4	Doesn't retain shape as well as the bentonite mix
	BCe	Bentonite, Sand, Methyl Cellulose	-	13	52	1	33	4	4	Extrudes and builds well
	KCe	Kaolinite, Sand, Methyl Cellulose	-	13	50	1	35	5	5	Extrudes and builds well
Natural soil	SCe	Soil, Cellulose	61			9	30	3	3	Hard to extrude
	SXg	Soil, Xanthan gum	64			9	27	2	5	Sticky while extruded, which allows cantilevering
	SGg	Soil, Guar gum	56			8	36	4.5	5	Extrudes and builds well
	SA	Soil, Sodium Alginate	64			9	27	5	5	Easily extrudable, successfully buildable, sample hardens quickly
	SLbg	Soil, Locust bean gum	64			9	27	5	5	Easily extrudable, successfully buildable, sample hardens quickly

*Based on qualitative assessment results, rated from 1(poor extrusion) to 5 (successful extrusion)

** Based on quantitative assessment, counting the number of vertically deposited layers wider particle size distribution. The maximum quantity of fibers for a mixture to be deemed extrudable and printable was 13% (total wt.%) for both the hemp (55% by total volume) and wheat straw (63% by total volume). The marked 8 mixtures were selected for further evaluation through the 3D additive manufacturing process using the printers due to its higher fiber content.

Table 2. Manual extrudability and buildability tests for the earth-fiber mixtures

	Mix design	Composition	Soil (wt%)	Fiber (wt%)	Additive (wt%)	Water (wt%)	Extrudability*	Buildability **	Qualitative Assessment Notes
Soil-fiber	SF	Soil, Hemp	43	2	-	55	5	5	Extrudes and builds well
	SSt	Soil, Wheat straw	43	2	-	55	5	5	Extrudes and builds well
	SSi	Soil, Sisal	43	2	-	55	-	-	Non extrudable
	SK	Soil, Kenaf	43	2	-	55	-	-	Non extrudable
	SB	Soil, Banana leaf	43	2	-	55	-	-	Non extrudable
Soil hemp	SLbgH1	Soil, Locust Bean Gum, Hemp Fiber	39	1	7	52	5	5	Extrudes and builds well
	SLbgH2	Soil, Locust Bean Gum, Hemp Fiber	38	2	7	53	5	5	Extrudes and builds well
	SLbgH3	Soil, Locust Bean Gum, Hemp Fiber	36	3	7	54	5	5	Extrudes and builds well
	SLbgH5	Soil, Locust Bean Gum, Hemp Fiber	30	5	6	58	5	5	Extrudes and builds well
	SLbgH7	Soil, Locust Bean Gum, Hemp Fiber	27	7	7	60	5	5	Extrudes and builds well
	SLbgH8	Soil, Locust Bean Gum, Hemp Fiber	27	8	5	60	5	5	Extrudes and builds well
	SLbgH10	Soil, Locust Bean Gum, Hemp Fiber	27	10	6	57	5	5	Extrudes and builds well
	SCAH13	Soil, Cellulose Sodium Alginate, Hemp Fiber	3	13	4	79	5	5	Extrudes and builds well, fiber clogging is initiated
Soil straw	SS1	Soil, Wheat straw, Cellulose, Alginate	49	3	2	24	5	5	Extrudes and builds well
	SS2	Soil, Wheat straw, Cellulose, Alginate	44	8	2	46	5	5	Extrudes and builds well
	SS3	Soil, Wheat straw, Cellulose, Alginate	3	13	4	79	5	5	Extrudes and builds well

Shown in Fig. 4, the mix designs generated exhibit a range of colors and textures, depending on the clay type in the engineered soil, or the natural soil. The resulting textures depended on fiber ratios, and the presence of sand in the soil.

4.2 Material Microstructural Imaging

Selected extrudable and buildable mixture from Sect. 4.1 were tested for their microstructural composition and macrostructural printability aspects.

Microstructural. The electron scanning conducted on four selected samples exhibit the improved matrix obtained by the soil-fiber-biopolymer composite. Shown in Fig. 5, the soil scans illustrate a clay plate structure, as anticipated from the clay-rich soils. For the engineered soil, Fig. 6 and Fig. 7 illustrate the uniformity of the composition, with the paste sand grain shape embedded within the matrix. The grains of sand are shown to be held by the clay-biopolymer paste, which forms a binding matrix. Lastly, the electron scanning of the soil-fiber-biopolymer composite, shown in Fig. 8, exhibits an

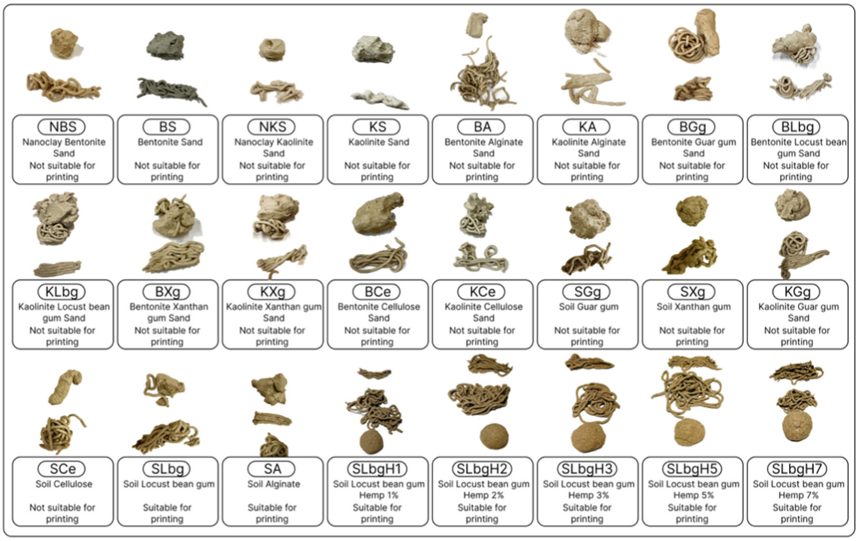

Fig. 4. The extrudability and buildability samples generated as part of this research, exhibiting the range of material colors and textures.

extremely heterogeneous composite, with fibers integrated throughout the matrix. This result, presumably explain the enhanced performance of the latter mixture in regards to strength (variable grain size) and printability (grain size smaller than the angular sand).

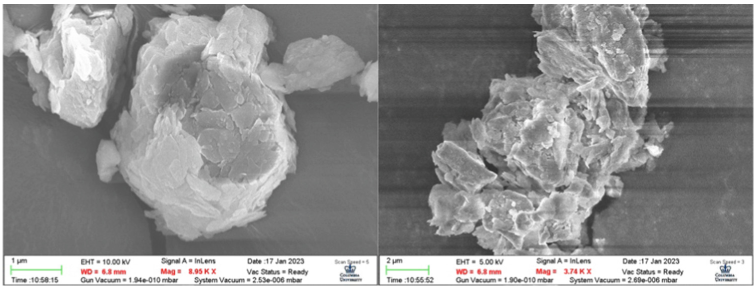

Fig. 5. Electron scanning of the soil used in this study, showing its clay mineral plates.

4.3 Machine Printability Tests

The selected mixtures from the manual extrudability and buildability tests were further evaluated through a 3D additive manufacturing process using the printers. While the soil-straw mixtures exhibited significant mold growth on the 24 h after printing, the soil-hemp mixtures experienced minimal molding within the drying process. This result might be explained by the fungal decay that is mostly attracted mainly to the cellulose components

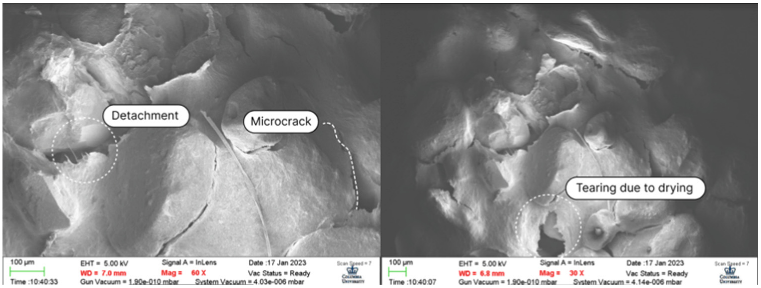

Fig. 6. Electron scanning of the Electron scanning of the sample BA (Bentonite, Sand, Alginate), showing significant detachments of the sand grains from the clay-additive paste.

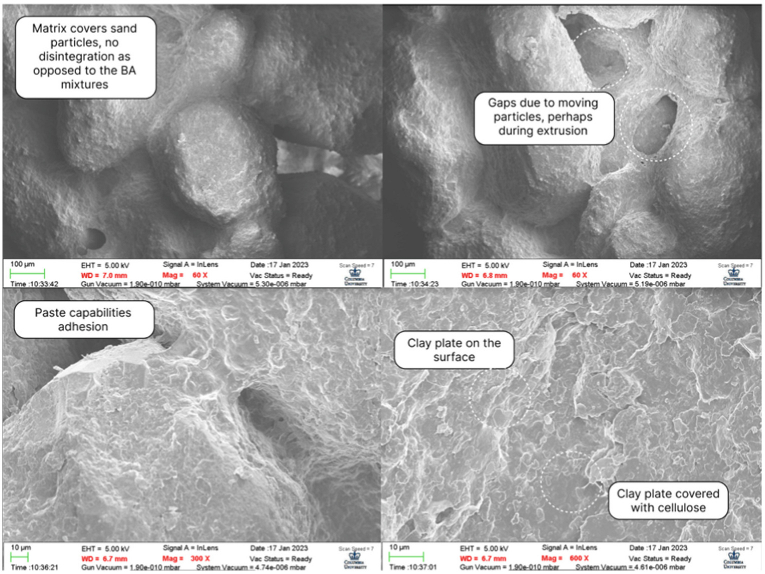

Fig. 7. Electron scanning of the KCe (Kaolinite, Sand, Cellulose), showing the matrix consistency and coating of the sand grains.

in the plant (Baldrian and Valášková 2008). The glucose units found in cellulose are consumed by the fungi agents to produce energy, and biomass in an anabolic process, while releasing CO_2 to the environment through catabolic processes (Lynd et al. 2002). Furthermore, the hemp clay exhibited higher ductility during the wet stage and decreased fragility in its dry form. The printed results, illustrated and interpreted in Fig. 9, exhibit the soil-straw and soil-hemp material as produced by the 3D printing machines.

Fiber Clog within Extrusion Flow Screw. As part of the experimental iterations, it was observed that fibers longer than 3 mm led to printing blockages due to clogging along the flow screw (observed in the WASP Delta 40100). Similarly, sand grains exhibited a similar phenomenon. The WASP Delta 40100 is engineered as a clay 3D Printer. Compared to clay particles, the sand grains were shown clog the edges of the screw due

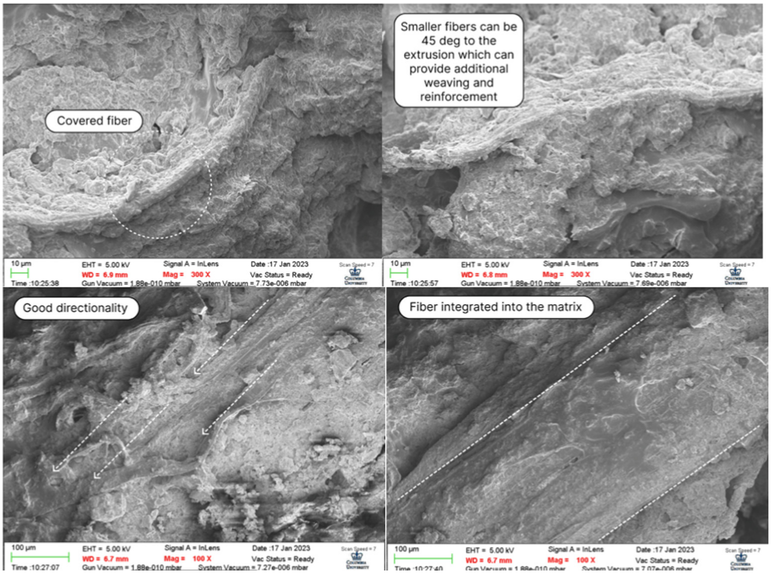

Fig. 8. Electron scanning of the SLbgH (Soil, Locust Bean Gum, Hemp), showing the comprehensive coating of the fibers by the paste, and the directionality of fibers according to the extrusion.

to their larger sizes as opposed to clay particles. Similarly, the 3mm hemp fibers were observed to clog in the screw system due to their length. Further observation also showed that the hemp fibers between the screw and the extruder wall caused friction that in turn clogged the machine.

Printing Parameters. The printing parameters were obtained for both mixtures, showing that different air pressure and layer heights were required, depending on the fiber type. It was observed that the first 3–4 layers should be printed in lower speed, to allow proper adhesion of the print "base". Once the first layers are successfully deposited, the speed is increased successfully to the machine's 100% rate. The printing process showed that the air pressure needed for the hemp clay mixture (5–6 psi) was much higher than the required pressure for light straw clay (3–4 psi). As a finer fiber, the hemp showed tendency to clog in small lumps within the mixture, which caused blockage of the printer if not mixed thoroughly.

5 Conclusions

This paper presents a series of experiments aimed to develop novel earth-fiber mix designs for 3D printed building materials. Earth materials are an emerging, sustainable alternative to cementitious materials because of their low embodied carbon, affordability, and indoor air quality characteristics. To date, however, most 3D printed earth research has been applied in nature, lacking consistent, reliable technical information related to material properties or design methodologies. For example, 3D printed earth mixture design research has been limited to mix designs that contain relatively low fiber content.

Fig. 9. Printed samples from the selected mix designs.

Using biopolymer binding agents and natural fibers, this project develops optimized mix designs for 3D printed earth while maximizing fiber content, and thus, carbon storage and thermal resistivity. Following a synthesis of the literature performance on fibers used for earth construction, the workflow approach developed as part of this work includes a manual extrudability and buildability assessment, a microstructural diagnosis using a scanning electron microscope, and a geometrical evaluation using machine printability tests.

The conclusions of the study point to enhanced mixtures of natural soils, infused with locust bean gum, alginate, and cellulose biopolymers, with up to 13% wheat straw or hemp fibers. The extrudability and buildability tests prove successful in projecting printability outcomes using two 3D printer types: a direct extrusion and delta screw extrusion machines. The final demonstration exhibits a successful implementation of earth-fiber materialities in 3D-printed applications in small scale samples.

This research critically catalyzes earth- and bio-based materials formulations and digital fabrication techniques. As a long-term deliverable, this work contributes to developing future fabrication techniques using carbon-storing earth composite wall assemblies, while also gearing towards a broader nonconventional geo-bio-based mixtures for digital construction.

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