International Conference on Non-conventional Materials and Technologies
NOCMAT 2022

TOWARDS 3D PRINTED EARTH- AND BIO-BASED INSULATION MATERIALS: A CASE STUDY ON LIGHT STRAW CLAY

Zackary Eugene Bryson[1], Wil V Srubar[2], Shiho Kawashima[3], and Lola Ben-Alon[1,*]

[1] *Graduate School of Architecture, Planning and Preservation, Columbia University, New York, NY, 10027*
[2] *Civil, Environmental, and Architectural Engineering, University of Colorado Boulder, Boulder, CO 80309*
[3] Civil Engineering and Engineering Mechanics, *Columbia University, New York, NY, 10027*
*To whom all correspondence should be addressed: rlb2211@columbia.edu

ABSTRACT
With a growing interest in sustainable construction practices and recent advances in the field of digital fabrication, 3D-printed earth has gained significant interest. However, research in 3D printed earth remains limited to cob, thus resulting in low thermal conductivity. Maximizing fiber content can provide greater thermal resistivity, while increasing carbon storage. This paper presents the development of 3D printed earth-fiber composite with fiber content ranging from commonplace cob (2% fiber) to newly developed printed light straw clay (64% fiber). This work contributes to critically needed advancements and framework for the development of low-carbon and high-performance materials for digital fabrication.

KEYWORDS
Earth materials; Bio-based materials; Light straw clay; 3D printing; Additive manufacturing.

THE CASE FOR 3D PRINTED EARTH-FIBER ASSEMBLIES

Earth architecture has been gaining renewed interest due its environmental benefits. In comparison to typical concrete building techniques, which is currently responsible for consuming 10% of global carbon emissions (Dixit et al. 2010); (Bruce King 2017), earth construction makes use of locally available and minimally processed materials, reducing embodied energy demand by 38–83%, and embodied climate change potential by 60–82% (Ben-Alon et al. 2021).

In terms of applicability for 3D printing fabrication, earth materials offer critical responses to challenges posed for 3D printed concrete. The integration of vertical reinforcement in the 3D printed concrete requires complex applications (Wangler et al. 2016) and dispersed short steel, glass, and polymer fibers were recently examined and still require further investigation (Panda et al., 2017; Bos et al., 2019). From an environmental standpoint, 3D printed concrete results in even higher carbon intensities than conventional concrete because it typically contains higher cement content in order to pass through the small pipe and nozzles at the print-head (Le et al. 2012). Printed earth is vernacularly practiced with micro-scale vegetable fibers that were shown to provide increased ductility while also maximizing carbon storage of the mix design (Miccoli, Müller, and Fontana 2014).

To date, however, 3D printed earth mixture design research has been limited to mix designs that contain low fiber content, as practiced in a vernacular method called cob. With high thermal capacity and low thermal resistivity, cob is limited by building codes to thick walls and is thus mostly suited warm-hot climates or as an assembly that is placed within the thermal envelope of a building (IRC, 2021). The most relevant studies introduce 3D printed cob using local subsoils that are qualitatively examined using simplified, prescriptive field tests, resulting in a recommended water content of 23-25% and 2% straw for reduced viscosity during the printing application (Gomaa, Jabi, Reyes, et al. 2021). Additional larger-scale

3D printed cob structures include experimental tests, artistic, and educational outreach activities that lack a thermal characterization and properties as required for code compliance (M. Marani 2018; 3D WASP 2019a; 2019b; Fratello and Rael 2020). These recent investigations of earth architecture, summarized in Figure 1, illuminate significant thermal and environmental opportunities; Whereas clay and cob mixtures are being increasingly well documented in the field of additive manufacturing (AM), reports of Light Straw Clay (LSC) still require further investigation.

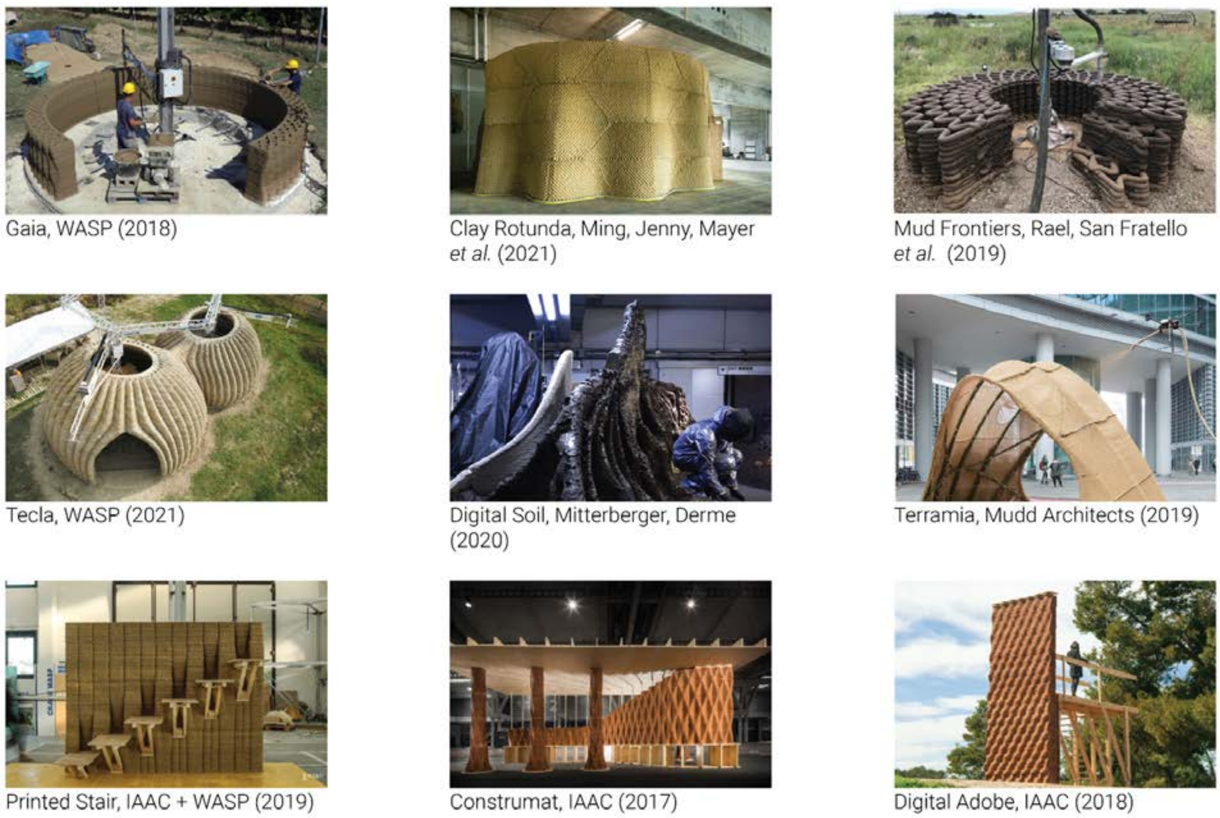

Figure 1: State of the art in digital fabrication for earth-based materials, ranging from 3D printing to drone-operated earth spraying technology.

In this study, the use of AM technology was employed to produced 3D printed lightweight earth-fiber building elements that provide higher thermal resistance when compared to cob. By maximizing fiber content in earth-based materials, this work produces improved thermal properties and an increase in carbon storage for 3D printed earth assemblies. The research framework included 3 major steps: (1) characterizing optimal mix designs and testing printability, (2) developing printing processing parameters and printing samples, and (3) testing the printed samples for their hard-state performance. This work includes an understanding of the structural and thermal benefits of increased fiber content while negotiating the printability of each mixture examined.

BACKGROUND ON 3D PRINTED EARTH

Conventional Earth Materials: Cob Vs. Light Straw Clay

Earth construction has been in practice since 7,000 BC (Pacheco-Torgal and Jalali 2012), and an estimated 30% of the world's population resides in earthen buildings to this day (Miccoli, Müller, and Fontana 2014). One of the most predominant vernacular techniques employed is cob (also known as Bauge (France), Lehmweller (Germany), Pasha (Turkey), Terre Crue (Italy), and Zabour (Yemen), to list a few). Historical cob buildings can be found globally (e.g., Europe, North and South America, New Zealand, Sahel, India, and China among others) which attests to the adaptive nature of the construction technique. Cob employs unbaked clay-rich subsoils, straw (or any other vegetable fiber such as hemp, pine, or rice husk), sand and water, with the occasional addition of stabilizers such as lime (for increased durability) and/or cow manure (as water repellant). The product of the mixture from these ingredients is used in a plastic state to build monolithic load bearing walls. Cob's simple recipe and ease with which a small to medium-sized building can be erected makes it an affordable and community-engaging building material, which contributes to its overall social benefits (Ben-Alon et al. 2019). However, due to its high mass capacity and low thermal resistivity, cob is mostly suited to warm-hot climates and requires walls as thick as 600mm to perform equally to conventional assemblies (Albert-Thenet and Samali B. 2017). Given the large amount of matter required for such thick walls, and the manual mixing process, cob is considered to be slow and labor intensive (Watson, MaCabe, 2011).

As opposed to cob, light straw-clay (also known as light clay, straw clay, slip straw, rammed straw and Leichtlehmbau in Germany), is an earth- and bio-based insulative infill method comprised of mostly fiber (usually straw) dampened with clay slurry (wet clay-rich soil), to be tamped within a structural frame (Ben-Alon et al. 2021). Light straw clay has a mean heat transfer coefficient of 0.531 W/m2K for a 120mm thick wall (Holzhueter and Itonaga 2017), making it a compatible insulation material with international energy code requirements. In terms of its environmental impacts, light straw clay was shown to outperform all other earth - and conventional – assemblies over its cradle to grave life cycle; Light straw clay had the lowest embodied and operational carbon due its low extractive constituent materials as well as thermal performance that reduces heating and cooling energy demand (Ben-Alon et al. 2021).

Figure 2: Cob structure made with formwork also known as shuttered-cob, light straw clay wall construction, and a clay-fiber composite.

Recent developments of cob and light straw clay composites, as shown in Figure 2, were developed for high-performance energy-efficient wall assemblies to "create a cob material that meets new thermal and structural building regulations (Goodhew, Boutouil, et. al., 2021). However, while these attempts use manual construction techniques, it is still limited in its slow and laborious construction process. Hence, emerging research that has evolved around 3D printed cob to increase pace and efficiency of construction should be extended to additional composite possibilities. 3D printed ecological insulation materials are still lacking and the use of light straw clay in additive manufacturing should be further developed and characterized by introducing higher fiber content into cob mixtures.

Earth-based digital manufacturing methods

3D printed earth has been executed for the large part through applied research, with cob and unfired clay as the most utilized materials. As shown in Figure 1, recent methods developed for digital manufacturing with earth include binder jetting with biodegradable hydrogel filler (Mitterberger and Derme 2020), robotically sprayed earth using temporary fabric formwork and embedded natural resin (Bravo and Chaltiel 2018), impact printing using robotic shooting of malleable discrete elements (Ming et al. 2021) and the most relevant work to this research - robotic additive manufacturing that is conducted in layers (Gomaa, Jabi, et al. 2021; Gomaa, Vaculik, et al. 2021; Alejandro Veliz-Reyes et al. 2018; Alhumayani et al. 2020; Gomaa et al. 2019; Perrot, Rangeard, et al. 2018; Dubor, Cabay, et al., 2018; Curth et al. 2020).

Similar to conventionally constructed earth materials, 3D printed cob walls are limited in their thickness ranging between 500-900mm, and the speed with which a structure can be built, often delayed by the necessary drying time. Preliminary research suggests that 3D printed cob also offers similar structural capacities to traditional cob assemblies; the compressive strength of traditional cob ranges between 0.4-1.35 MPa, while 3D printed counterparts averaged 0.87 MPa (Gomaa, Vaculik, et al. 2021), giving 3D printed cob the capacity to act as a load bearing assembly for 1-2 stories structures. In their work, Perrot, Rangeard, and Courteille (2018) improved the fresh-state structural properties of printed earth by adding alginate biopolymer. Their work also indicated the added benefit of printing with a rectangular cross section, which rids any air pockets and irregularities in the printed volume, resulting in a 15% increase in compressive strength.

The thermal performance of 3D printed cob has been documented by isolating a single cob mixture and testing varied geometric extrusions (Gomaa et al. 2019). Using a Heat Flow Meter, this work showed that the precision offered by the digital construction technology reduced thermal conductivity by 30%, due to the design of air pockets. Furthermore, air pockets filled with straw were shown to further decrease conductivity by 15%. In terms of their environmental impacts, cob material consumption can be reduced due to the precision offered by digital fabrication tools and their ability to embed cavities, effectively reducing material quantities (Alhumayani et al. 2020).

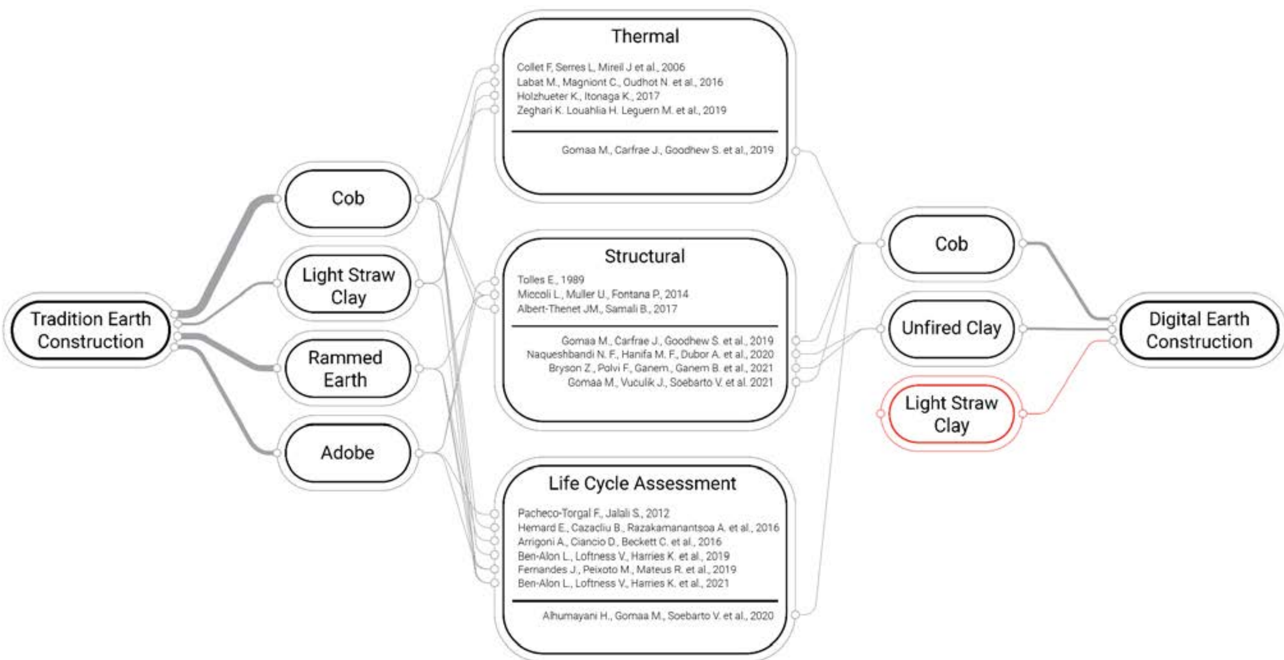

Figure 3: State of the art in additive manufacturing for earth materials, in comparison to conventional construction, comparing techniques and literature available.

As opposed to conventionally constructed earth materials, 3D printed earth consists of mixtures with higher water content to reduce viscosity and facilitate the material extrusion, with 23-25% water (Alhumayani et al. 2020). Previous research has shown challenge in increasing fiber content over 2% fiber in weight due to extrusion difficulties and increases viscosity that results in printing malfunction and clogging (Veliz-Reyes A et al. 2018). Additional methods which introduce combinations of printed cob and fiber filling in cavities show promise for thermal regulation, and preliminary testing has been conducted (M. Marani 2018;

Holzhueter and Itonaga 2017). Due to its anticipated high ductility and flexural strength, 3D printed light straw clay is explored in cantilevered structures that pose a major challenge in 3D printed earth, especially during the printing process. Light straw clay may reduce the need for temporary supports during the printing process, minimizing the use of wood or styrofoam supports that were previously used to assist in the printing of arches and Vaults (Veliz-Reyes A et al. 2018).

3D printed earth requires multiple avenues for continued development and much of the 3D printed earth research remains elementary and often results in straight wall extrusions much like vernacular cob construction. Additionally, existing studies limit their research to the use of singular mixtures (Figure 3), although composite assemblies with material combination may provide better thermal and structural response to dynamic performance needs. To address this gap, this research develops extrudable earth-fiber mixtures with bio-based additives, coined as *3D Printed Lite Clay*, to provide enhanced thermal and structural properties as opposed to 3D printed cob.

MATERIALS AND METHODS

To characterize cob and light straw clay 3D printed assemblies, it is necessary to classify the constituent materials and develop optimal mix designs while accounting for both wet- and dry-state properties. Shown in Figure 4, the procedure used in this work was initiated with constituent materials characterization for densities, grain distribution, and mineralogical content, while obtaining mix designs for increasing fiber contents. Each mixture was then tested for its printability (extrudability and buildability) using a manual and robotic extruder to select optimal mixtures for printing. Lastly, mixtures were characterized for their dry thermal and compressive performance using the test methods described in the subsequent sections.

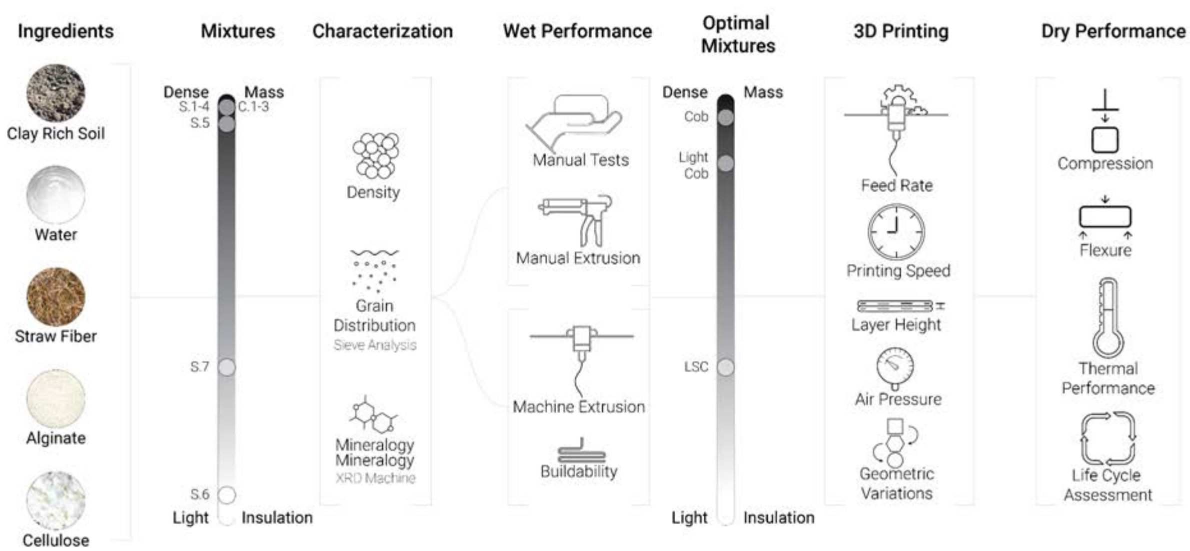

Figure 4: Research procedure: mixture design with various fiber content, 3D printing processing parameter development, and characterization of wet and dry performance.

The soil used in the research was of a dark grey-brown composition, sourced from a local quarry (Goshen, New York USA). Wheat straw was used as a fiber, extracted from Dutchess County, NY. Sodium alginate and microcrystalline cellulose are used as additives, both produced within the US with constituent materials sourced from Europe.

Material Characterization

Particle-Size Analysis of Soil

A manual sedimentation test (also known as the "shake test" for soil composition) was conducted to characterize the soil. The medthod provides a first pass quantitative measurement of the fine gravel, sand, silt, and clay fractions within an existing soil sample (NZS 4298, 1998). As part of the test, a loose sample of soil is soaked into water within a transparent container of approximately 500 ml. The container is vigorously shaken for 1-2 minutes, after which it is left undisturbed until the test has been completed. Readings are taken 1 minute after shaking to measure the combined layers of fine gravel and sand, 45 minutes after shaking to measure the combined layers of sand and silt, and 24 hours after shaking to measure the layer of clay. The layers are measured in height as a percentage of total soil height.

The raw soil was further characterized according to the Grain Size Distribution Test Data –ASTM D2487-11 and ASTM D422. Sieve analysis was conducted on a sample of the harvested soil to determine the distribution of particle sizes, referred to as the gradation of the material. The aggregate gradation was used to assess the effects on the engineering properties (e.g., stiffness, resistance to deformation, density, etc.) of mixtures. Two soil samples were evaluated, the first one being raw soil which had been collected on site, while the second was an already sifted sample which had already been tested in mixtures and proved to be extrudable, meaning the composition of the resultant sifted mixture had a grain size distribution fine enough to pass through the 6mm nozzle of the printing machine. Both samples were left to air-dry for a period of 21 days, and 1000g were collected from both for testing. The sieve analysis was conducted using a set of eight sieves which range from no. 4 (retaining particles greater than 4.75mm in diameter) to no. 200 (only allowing particles less than 75 µm in diameter to pass through, which are defined as the fines, or the clay and silt present in the samples). The soil was placed on the top sieve with the others descending in size stacked below with a collecting pan at the bottom and was shaken manually for 90 seconds. The collected soil retained by each sieve was recorded and the process was repeated for the second sample.

In addition to these two first pass tests, subsoil samples were laboratory tested for their grain distribution and soil composition, including particle size analysis, plastic limit and liquid limit (plasticity), proctor test (optimum moisture content), mineralogical analysis using XRD, and chemical analysis (salts, pH, organic matter, carbonates). The performance of the applied field tests was juxtaposed against the scientific lab inputs to provide insights about the accuracy, prioritization, and possible improvements to the field tests.

Soil Mineralogy

Crystallographic analysis through X-Ray Diffraction (XRD) was conducted through the use of the PANalytical Xpert3 Powder XRD. The test was pursued as to find the primary minerals which constitute the soil samples collected. The analysis highlighted the major crystalline phases found in the sample listed in order of their profusion. Samples of 50 mg were prepared and measured in the -173-400°C range in an Antron-Paar TTK 450 stage.

Mixture Processing and Mixture Proportioning

The wheat straw was processed through a Vitamix Blender (Vitamix 7500 machine, Vitamix Corp., Cleveland, OH, USA) in order to obtain the desired length, averaging between 0.5 mm to 4 mm. The shredded fibers were sifted using a sieve with an opening size of 1.18 mm in order to ensure a degree of consistency in the final product and to minimize clogging during the printing process. Fiber was added to the mixtures in varying amounts to obtain the three desired mixtures, cob, light cob and light straw clay.

Earth-fiber mixtures were proportioned to assist with green strength and printability (Table 1). The application and interest in cellulose fibers for printing purposes is multifaceted and largely due to its low density, high degrees of stiffness and high strength. Hydrogen bonds formed in the structure of cellulose provide a restricted motion of water, increasing the viscosity and ensuring a homogeneous mixture (Gauss, Pickering, and Muthe 2021). Food-grade sodium alginate (E401), extracted from brown seaweed (sea kelp), was incorporated into the mixtures used for printing. Water-soluble alginate is a biodegradable, low-cost and bio-compatible polymer which has the ability to form hydrogen bonds with other materials. When combined with cellulose, this composite material forms a cross-linking scaffold which increases the viscosity of the printing material while providing high printing resolution and increase in shape retention (Mallakpour, Azadi, *et al.,* 2021).

Manual extrusion and 3D Printing

Once the mixtures were formulated, printability aspects such as extrudability (the ability of the fresh material to pass through the small pipe and nozzles at the print-head) (Malaeb, AlSakka, and Hamzeh 2019), and buildability (the resistance to deformation of a printed layer to the shear stress due to its own weight and that of subsequent layers) are necessary to characterize mixtures for 3D printing (Le, Austin, et. al., 2012). Additionally, the mixture must have sufficient stiffness to resist global buckling (Tay, Qian, Tan, 2019).

These initial tests, conducted on ten earth-additive mixtures were tested with varying additives and clay/soil contents, as shown in table 3, provided qualitative insights into the usability of preliminary mixtures, which were optimized before taken to the machine. Of the samples analysis manually, two were chosen as the base for further testing using the PotterBot 3D to establish the three desired fiber contents for cob, light cob and LSC.

The apparatus employed a manual extrusion caulk gun (Albion Engineering Company B12S20) as well as a PotterBot 3D printing machine with 6 mm nozzle (by 3D Potter ®), which uses a cartesian system with printing head z-axis movement and printing platform movement in the x and y axes. The use of the 6 mm nozzle diameter ensured a reduced risk of clogging during the printing process given the high fiber content in the mixtures tested. Manual tests were conducted using a caulk gun aimed to identify solely the extrudability of a mixture from a 5mm nozzle. The manual extrusions were assessed qualitatively by observing the smoothness of extruded matter from the syringe of the caulk gun. Extrudability has been previously described as "the ease with which concrete can continuously be pushed out of a nozzle". Thus, it was assumed that this qualitative assessment is useful in determining the printability of a material as a function of the shape retention of a printed specimen.

Machine Parameters, Printability, and Buckling

The buildability of a mixture refers to the ability of printed layers to support themselves, as well as succeeding layers above it. The method used to test each mixture was to print a single layer wall 100 mm in length and count the printed layers before any noticeable deformation or collapse happens. The more layers that can be stacked on top of one another, the higher the buildability of a mixture is. The aim of this test was to evaluate the height each mixture could reach before any deformation would occur and evaluate the time it took from the first signs of fault to the point of collapse. This second value relates to the ductility of the materials. A layer height of 3.6 mm and printing speed of 20 mm/s were utilized. The printing tests to determine buildability used simple cylinder geometries in single layer extrusions to allow geometrical simplicity. Then, extrusions with inclined faces, ranging from 15-30 degrees were conducted to understand the extents to which each material can be cantilevered without the use of additional supports.

Structural Performance

Compressive and three-point flexural testing was conducted to understand the benefits of fiber additives in various content ratios for 3D printed earth-based mixtures. Mechanical testing was performed using an electromechanical material testing frame (Criterion C43.104, MTS Systems, Eden Prairie, M). The machine offered a maximum load capacity of 30kN and was operated using a displacement-controlled rate of 1mm/min.

RESULTS

Material Characterization

Particle-Size Analysis of Soil

The results of the grain size distribution test, shown in Table 1, indicate that the soil used for printing consists of 10% clay and silt. This result is high for the non-sifted soil when compared to the soil which is initially sifted for printing. This result is in large part due to the initial processing of the harvested raw soil which removed the large particles greater than 1.22mm in size, which often contain clay that is adhered to larger aggregates and is not separated when manual sifted. The agitation provided through this testing method indicated that a large amount of clay goes unused when preparing materials for printing from raw soil. The results indicate that the non-sifted soil is well-graded, with mostly gravel and sand content.

Table 1: Percentage of retained soil from sifted sample for the incorporated soil.

Sift Size	Microns	Opening (mm)	Retained Matter (g)	Percentage
4	4750	4.75	0	17.6
8	2360	2.36	0	23.7
16	1180	1.18	0.09	18.8
25	710	0.71	110	9.25
30	600	0.6	228	4.49
50	300	0.3	289	5.24
100	150	0.15	211	5.74
200	75	0.075	102	5.09
Silt/Clay	> 75.0	> 0.075	59.91	9.58

Soil Mineralogy

XRD patterns of the sifted and ground soil sample show the high intensity and broad peaks of silica in the form of α-quartz. It can be observed that the peaks of quartz overlap with the peaks of other minerals in the sample and so the other phases are not discernible. Peaks of other clay minerals such as kaolinite and illite can be observed with lesser intensity, as seen in Table 2. The results of the XRD analysis alongside the results obtained from the sieve analysis indicate that the soil used for printing has a lower than anticipated clay presence.

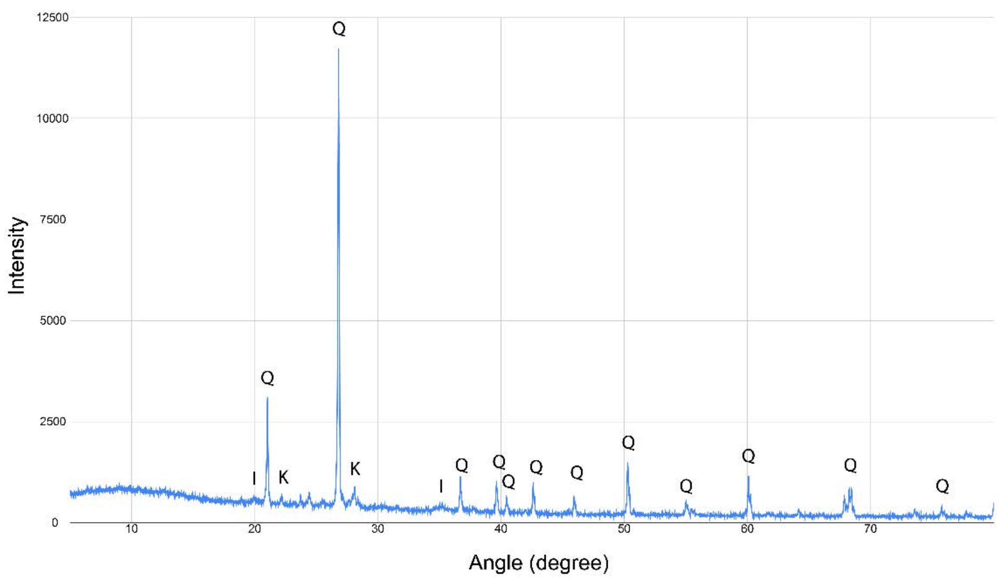

Figure 5: XRD pattern of soil used for 3d printing. Soil minerals are marked as [Q] for quartz, [K] for kaolinite, and [I] for illite.

Mixture Printing Process Parameters

Manual extrusion of various mixtures and varying fiber contents

Ten mixtures were examined for their extrudability, as detailed in Table 2 (images in Figure 6) . Examining diverse types of soils and clays as binders and increasing the amount of fiber (posing the most threat to extrudability), the other additives were adjusted in order to ensure appropriate viscosity. Using visual inspection, the extrudability was measured and reported as satisfactory if the mixture was capable of being pushed out continuously without clogging. Mixtures S.4 and S.5 were deemed the most successful and were used to move forward as the base mixture. It was observed in the sequence of testing that blockage was more significant as fiber content was increased but when using finer fibers, which were shredded and sifted using a 60um sieve, the extrudability was improved. Adding higher contents of alginate, while adjusting water content, improved extrudability as well as viscosity and flowability. Of the samples tested, the ones using soil as a binder outperformed the clay-based mixtures in terms of extrudability, potentially due to the inert and reduced overall surface interactions in the mixture.

Table 2: Initial clay-additive and earth-additive mixtures, testing manually

Clay Mixture	Clay or Subsoil (g)	Sand (g)	Fiber (g)	Water (g)	Admixture (g)	Manual Extrusion Results
C.1	25.0 - Red Clay	75.0	2.02	24.8	0.58g cellulose	Intermediate extrudability due to coarse sand size
C.2	17.2 - Red Clay	53.7	2.08	25.5	2.20g Cellulose	Intermediate extrudability due to high content of sand
C.3	17.1 - White Clay	53.6	2.05	25.4	2.02g Cellulose	High extrudability
S.1	50.0	25.3	2.01	25.2	0.55g Cellulose	Intermediate extrudability
S.2	33.0	40.0	2.00	22.0	1.5g Cellulose	Intermediate extrudability
S.3	163	0.00	0.00	70.1	0.85g Alginate	Intermediate extrudability
S.4	34.0	0.00	1.02	16.8	0.35g Alginate 0.25g Cellulose	High extrudability
S.5	63.1	0.00	5.06	31.4	0.72g Alginate 0.54g Cellulose	High extrudability
S.6	0.00	0.00	10.4	48.0	0.84g Alginate 0.52g Cellulose	Very high extrudability
S.7	"Sprinkled dash"	0.00	5.16	30.0	0.96g Alginate 0.54g Cellulose	High extrudability

*Food-grade sodium alginate (E401), extracted from brown seaweed (sea kelp)
** Microcrystalline Cellulose

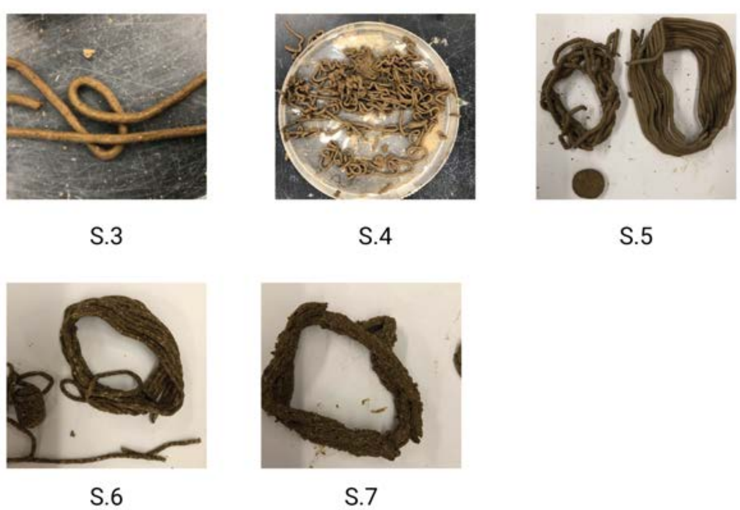

Figure 6: Extrusion tests of subsoil mixtures

Of the tested mixtures, 3 optimal mix designs were extracted to correspond with constituencies of cob, light cob, and light straw clay, as detailed in Table 3.

Table 3: Selected mixtures for printing.

	Clay-Rich Soil	Fiber (g)	Cellulose (g)	Alginate (g)	Water(g)
Cob	65.0	4.00	1.0	1.0	32.0
Light Cob	65.0	12.0	0.99	1.35	67.5
Light Straw Clay	65.0	244	36.7	46.3	1480

Machine Parameters, Printability, and Buckling

The three mixtures detailed in Table 3 were further tested for their buildability and machine parameters. In the 3.5 mm layer heights evaluated, cob showed the highest buildability. Cob specimens showed failure starting on average on the 16th layer with a noticeable collapse on the 21st layer. The light cob mixture exhibited failures starting on averagely on the 14^{th} layer, but did not collapse until at least the 23rd layer. This might be a result of the fibers' ability to render the mixture more elastic and able to withstand more error in the printing process. Light straw clay showed the widest gap between failure start and noticeable collapse, starting on average on the 12th layer and collapsing on the 21st layer. This result might indicate the enhanced ductility due to the added fiber.

Figure 7: Printing in progress of angled tests and single layer buildability test.

Further testing in determining the buildability of a material was conducted by printing each mixture at varying angles (30°, 20°, 15°) without the use of external supports, Figure 7. Each mixture was assessed beginning with the 30° angle tests. The results were as expected after having conducted the initial buildability testing, with the exception of the light cob which outperformed the cob and light straw clay. Although 30° was the maximum tilt possible for each mix, the light cob was able to reach twenty-seven layers before significant buckling, while cob only reached 21 and light straw clay did not make it past 6 layers before significant slouching occurred and subsequent layers could not adhere to those already printed.

Structural Performance

Compressive Strength Results

Samples prepared for compressive strength testing were cast in a 63.5mm x 63.5mm x 63.5mm formwork and left to dry for a minimum of 14 days. Given inconsistencies in the drying process and imperfections left in the cast specimen, a sharp blade was used to level-out any issues on the contact surfaces which may introduce stress concentration. The three samples from Table 2 were analyzed, showing that greater soil content improves compressive strength, whereas reversely, increasing the straw and alginate content reduces the compressive strength of the material, as seen in Figure 8. The highest compression strength value obtained was from the cob sample at 2.863 kN while the lowest value from the LSC sample was 1.608 kN. These results remain consistent with expectations and suggest that the cob mixture would be better applied as the structure of a 3D building, whereas the LSC, which is used as an insulative material, is not required to carry any load.

Figure 8: compressive and flexural strength tests using MTS Criterion C43 Electromechanical Testing Machine.

Flexural Strength Testing

Samples prepared for flexural strength testing were cast in a 178mm x 50mm x 50mm formwork and left to dry for a minimum of 14 days. Similarly, to the samples used for compressive testing, the specimens were smoothened to obtain accurate readings that would not be jeopardized by uneven surface contact with the machine. Three-point flexural tests for determining the ultimate flexural strength of each mixture were performed with a consistent span of 125mm and constant speed of 1.0mm/min until the point of fracture. There was a definitive upward trend in flexural strength as the fiber content was increased and soil content decreased. As shown in Table 4, the highest flexural strength value obtained was that of the LSC at 0.336 MPa. The lowest obtained strength was from the cob sample with a value of 0.038MPa. The data shows a definitive increase in strength as fiber content is increased. (Further testing could be performed with varying spans and more tests for each mixture to ensure consistency).

Table 4: Structural test results, measured in MPa.

	Cob	Light Cob	Light Straw Clay
Compression	0.710 MPa	0.653 MPa	0.399 MPa
Flexure	0.038 MPa	0.343 MPa	0.366 MPa

CONCLUSION AND SIGNIFICANCE

This research presents a novel development of earth-fiber composites for 3D printing applications. By incorporating earth (mass) and vegetable fibers (insulation), the proposed development aims to provide high-performance assemblies compared to conventional uninsulated 3D printed materials. Digital fabrication has been widely introduced thus far in the field of cement-based materials. Earth-based materials offer shorter supply chains that could make digital fabrication a promising sustainable solution. Earth-fiber mixtures require minimal processing while sourcing raw materials from the construction site. Earth- and fiber-based building materials substantially reduce transportation, chemical treatments, excess manufacturing, warehouse storage, and intermediary storages that are inextricably intertwined with conventional highly-processed materials. The long-term implications of this research lie in the intersection of natural, low-carbon materials and their impacts on advanced manufacturing.

Developing a new categorization system for earth-based mixtures to be applied in the field of additive manufacturing would greatly improve the efficiency with which buildings are printed and would define new aesthetic qualities unique to the field. By making distinctive separation between structural members in a building versus insulating elements, specific material mixtures could be applied within the printing process and improve both the structural behavior and the thermal properties. Further work is currently under development by the authors to characterize the insulative properties and life cycle of a range of earth-fiber composites.

ACKNOWLEDGEMENT

The work in this paper was partially supported by NSF award number # 2134488.
The authors would like to thank Joshua C. Jordan, the Director of the fabrication spaces and services for Columbia GSAPP, Mark Taylor, Director of Facilities, and Yonah Elorza, Making Studio Manager, for their continuous support, technical assistance, and dedication throughout the project.
The authors acknowledge the contribution of additional graduate research students at the Natural Materials Lab: Reem Makkawi and Saba Ardeshiri, to the project.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest associated with the work presented in this paper.

DATA AVAILABILITY

All necessary data is found in this paper.

Bibliography

3D WASP. 2019a. “3D Printed Earth Wall with Embedded Staircase.” 2019. https://www.3dwasp.com/en/3d-printed-wall/.

———. 2019b. “D Printed House TECLA: Eco-Housing,.” 2019. https://www.3dwasp.com/en/3d-printed-house-tecla/.

Alhumayani, Hashem, Mohamed Gomaa, Veronica Soebarto, and Wassim Jabi. 2020. “Environmental Assessment of Large-Scale 3D Printing in Construction: A Comparative Study between Cob and Concrete.” *Journal of Cleaner Production* 270 (October). https://doi.org/10.1016/j.jclepro.2020.122463.

Ben-Alon, L., V. Loftness, K.A. Harries, and E. Cochran Hameen. 2021. “Life Cycle Assessment (LCA) of Natural vs Conventional Building Assemblies.” *Renewable and Sustainable Energy Reviews* 144 (July). https://doi.org/10.1016/j.rser.2021.110951.

Ben-Alon, Lola, Vivian Loftness, Kent A. Harries, Gwen DiPietro, and Erica Cochran Hameen. 2019. “Cradle to Site Life Cycle Assessment (LCA) of Natural vs Conventional Building Materials: A Case Study on Cob Earthen Material.” *Building and Environment* 160 (August). https://doi.org/10.1016/j.buildenv.2019.05.028.

Bos, F. P., E. Bosco, and T. A. M. Salet. 2019. “Ductility of 3D Printed Concrete Reinforced with Short Straight Steel Fibers.” *Virtual and Physical Prototyping* 14 (2): 160–74. https://doi.org/10.1080/17452759.2018.1548069.

Bravo, Maite, and Stephanie Chaltiel. 2018. “Monolithic Earthen Shells Digital Fabrication: Hybrid Workflow.” In *Humanizing Digital Reality*, 509–21. Singapore: Springer Singapore. https://doi.org/10.1007/978-981-10-6611-5_43.

Bruce King. 2017. The New Carbon Architecture: Building to Cool the Climate. New Society Publishers.

Curth A, Darweesh B, Arja L, and Real R. 2020. “Advances in 3D Printed Earth Architecture: On-Site Prototyping with Local Materials.” *BE-AM Symposium*, November.

Dixit, Manish Kumar, José L. Fernández-Solís, Sarel Lavy, and Charles H. Culp. 2010. “Identification of Parameters for Embodied Energy Measurement: A Literature Review.” *Energy and Buildings* 42 (8). https://doi.org/10.1016/j.enbuild.2010.02.016.

Dubor, Alexandre, Edouard Cabay, and Angelos Chronis. 2018. “Energy Efficient Design for 3D Printed Earth Architecture.” In *Humanizing Digital Reality*, 383–93. Singapore: Springer Singapore. https://doi.org/10.1007/978-981-10-6611-5_33.

Fratello, Virginia San, and Ronald Rael. 2020. “Innovating Materials for Large Scale Additive Manufacturing: Salt, Soil, Cement and Chardonnay.” *Cement and Concrete Research* 134 (August): 106097. https://doi.org/10.1016/j.cemconres.2020.106097.

Gauss, Christian, Kim L. Pickering, and Lakshmi Priya Muthe. 2021. “The Use of Cellulose in Bio-Derived Formulations for 3D/4D Printing: A Review.” *Composites Part C: Open Access* 4 (March): 100113. https://doi.org/10.1016/j.jcomc.2021.100113.

Gomaa, Mohamed, Jim Carfrae, Steve Goodhew, Wassim Jabi, and Alejandro Veliz Reyes. 2019. “Thermal Performance Exploration of 3D Printed Cob.” *Architectural Science Review* 62 (3). https://doi.org/10.1080/00038628.2019.1606776.

Gomaa, Mohamed, Wassim Jabi, Alejandro Veliz Reyes, and Veronica Soebarto. 2021. “3D Printing System for Earth-Based Construction: Case Study of Cob.” *Automation in Construction* 124 (April). https://doi.org/10.1016/j.autcon.2021.103577.

Gomaa, Mohamed, Jaroslav Vaculik, Veronica Soebarto, Michael Griffith, and Wassim Jabi. 2021. “Feasibility of 3DP Cob Walls under Compression Loads in Low-Rise Construction.” *Construction and Building Materials* 301 (September). https://doi.org/10.1016/j.conbuildmat.2021.124079.

Goodhew, S., Boutouil, M., Streiff, F., Le Guern, M., Carfrae, J., & Fox, M. (2021). Improving the thermal performance of earthen walls to satisfy current building regulations. *Energy and Buildings*, *240*, 110873.

Holzhueter, Kyle, and Koji Itonaga. 2017. “The Potential for Light Straw Clay Construction in Japan: An Examination of the Building Method and Thermal Performance.” *Journal of Asian Architecture and Building Engineering* 16 (1). https://doi.org/10.3130/jaabe.16.209.

International Code Council, Inc. (2021). *2021 Irc: International residential code for one- and two-family dwellings*.

Albert-Thenet, J-M., and Samali B. 2017. “THE EARTHQUAKE RESISTANCE OF COB STRUCTURES.” Sydney.

Le, T. T., S. A. Austin, S. Lim, R. A. Buswell, A. G. F. Gibb, and T. Thorpe. 2012. “Mix Design and Fresh Properties for High-Performance Printing Concrete.” *Materials and Structures* 45 (8): 1221–32. https://doi.org/10.1617/s11527-012-9828-z.

M. Marani. 2018. “The Gaia House Is a 3D-Printed Prototype Made of Biodegradable Materials.” The Architects Newspaper. 2018. https://www.archpaper.com/2019/04/gaia-house-facadesplus/.

Malaeb, Zeina, Fatima AlSakka, and Farook Hamzeh. 2019. “3D Concrete Printing.” In *3D Concrete Printing Technology*, 115–36. Elsevier. https://doi.org/10.1016/B978-0-12-815481-6.00006-3.

Mallakpour, Shadpour, Elham Azadi, and Chaudhery Mustansar Hussain. 2021. “State-of-the-Art of 3D Printing Technology of Alginate-Based Hydrogels—An Emerging Technique for Industrial Applications.” *Advances in Colloid and Interface Science* 293 (July): 102436. https://doi.org/10.1016/j.cis.2021.102436.

Miccoli, Lorenzo, Urs Müller, and Patrick Fontana. 2014. “Mechanical Behaviour of Earthen Materials: A Comparison between Earth Block Masonry, Rammed Earth and Cob.” *Construction and Building Materials* 61 (June). https://doi.org/10.1016/j.conbuildmat.2014.03.009.

Ming, Coralie, Ammar Mirjan, Jesús Medina Ibáñez, Fabio Gramazio, and Matthias Kohler. 2021. “Impact Printing.” *3D Printing and Additive Manufacturing*, September. https://doi.org/10.1089/3dp.2021.0068.

Mitterberger, Daniela, and Tiziano Derme. 2020. “Digital Soil: Robotically 3D-Printed Granular Bio-Composites.” *International Journal of Architectural Computing* 18 (2): 194–211. https://doi.org/10.1177/1478077120924996.

New Zealand Standards, NZS 4298: Materials and Workmanship For Earth Buildings. 1998. (pg 7)

Pacheco-Torgal, F., and Said Jalali. 2012. “Earth Construction: Lessons from the Past for Future Eco-Efficient Construction.” *Construction and Building Materials* 29 (April). https://doi.org/10.1016/j.conbuildmat.2011.10.054.

Panda, Biranchi, Suvash Chandra Paul, and Ming Jen Tan. 2017. “Anisotropic Mechanical Performance of 3D Printed Fiber Reinforced Sustainable Construction Material.” *Materials Letters* 209 (December): 146–49. https://doi.org/10.1016/j.matlet.2017.07.123.

Perrot, A., D. Rangeard, and E. Courteille. 2018. “3D Printing of Earth-Based Materials: Processing Aspects.” *Construction and Building Materials* 172 (May). https://doi.org/10.1016/j.conbuildmat.2018.04.017.

Veliz-Reyes A, Gomaa M, Chatzivasileiadi A, and Jabi W. 2018. “Computing Craft: Early Stage Development of a Robotically-Supported 3D Printing System for Cob Structures.”

Alejandro Veliz-Reyes, Mohamed Gomaa, Aikaterini Chatzivasileiadi, Wassim Jabi, and Nicholas Mario Wardhana. 2018. “Computing Craft: Early Stage Development of a Robotically-Supported 3D Printing System for Cob Structures.” *Education and Research in Computer Aided Architectural Design in Europe* 1.

Wangler, Timothy, Ena Lloret, Lex Reiter, Norman Hack, Fabio Gramazio, Matthias Kohler, Mathias Bernhard, et al. 2016. "Digital Concrete: Opportunities and Challenges." *RILEM Technical Letters* 1 (October): 67. https://doi.org/10.21809/rilemtechlett.2016.16.

Watson, L., & McCabe, K. 2011. The cob building technique. Past, present and future. Informes de la Construccion-Revista, 63(523), 59.