BioMatters

The Robotic 3D-Printed Biodegradable Wood-Based Formwork for Cast-in-Place Concrete Structures

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1 BioMatters showcasing the 3DP wood-based biomaterial formwork for concrete casting.

ABSTRACT

'BioMatters' explores methods of creating wood-based material for 3D Printing freeform concrete formwork. The concrete industry is widely acknowledged as a significant contributor to waste, pollution, and resource consumption. Typical concrete formwork, which constitutes 40% of the overall expenses in concrete construction, is a significant source of waste. Recent 3D printing advancements in concrete formwork offer increased design flexibility, significantly reduced concrete consumption, minimal material waste, and improved productivity. This research project represents a pioneering advancement in 3D printing formwork by investigating robotic 3D printing methods with wood-based materials that are fully biodegradable, reusable, and recyclable. The paper presents a novel method of coupling robotic 3D printing of wood-based material with incremental set-on-demand concrete casting to create zero-waste, freeform concrete structures. Here, the concrete takes its shape from the 3D-printed wood formwork and, at the same time, concrete stabilizes the 3D printed wood to prevent its deformation on a larger scale. Once the concrete is cured, the formwork is removed and is fully recycled by grinding and rehydrating the material with water, thus creating a nearly zero-waste formwork solution. The method is investigated involving the design and fabrication of a pair of 1.8-meter-high structural columns. This project focuses on utilizing the material from previous 3D printed formwork for each subsequent column, to evaluate the reusability of the material. The project explores various aspects, including sequential rebar integration, the correlation between the geometric properties of the 3D printed formwork, and the rheology hydrostatic pressure of the concrete mix in relation to material design.

INTRODUCTION

ADDITIVE MANUFACTURING FOR CONCRETE FORMWORK

Over the last few centuries, the construction industry has been highly dependent on concrete. For construction, in particular, concrete formwork contributes to 30% of waste in total construction (Cheng et al. 2022). Concrete formwork plays a significant role in the expenses of concrete construction. Concrete formwork represents 40% of overall construction expenses (Cheng et al. 2022). Timber formwork is one of the most commonly used formwork types for casting. However, it can be reused only for casting similar geometries, meaning more formwork is required for a flexible design, leading to additional material needs, resulting in material wastage (Li et al. 2022).

Recent advancements in additive manufacturing (AM) technologies, specifically in fused filament fabrication (FFF) and liquid deposition modeling (LDM), has expanded the geometric possibilities for concrete formwork (Jipa and Dillenburger 2022). Fused filament fabrication is a 3D printing (3DP) technique where a thermoplastic material is melted and extruded through a nozzle, layer by layer, to create the desired components. Liquid deposition modeling, on the other hand, involves the deposition of liquid materials, such as resins or polymers, layer by layer to build the desired components. These advancements in additive manufacturing have been demonstrated in the construction industry extensively. A significant challenge to overcome in this 3DP formwork research has been to develop an approach to control hydrostatic pressure. Hydrostatic pressure refers to the constant lateral pressure exerted by gravity on the formwork when the fluid is in equilibrium. Hydrostatic pressure can break the 3D-printed formwork, while casting concrete can lead to failures. Researchers have developed methods for 3DP formwork in relation to hydrostatic pressures. For example:

- The 'Additive Thermoplastic Formwork for Freeform Concrete Columns' project investigates the 3DP of lightweight concrete formwork for structural concrete columns. This research utilizes FFF 3D printing of Poly-Lactic Acid (PLA) thin-shell formwork, Polyvinyl Alcohol (PVA) formwork and robotic 3DP Polyethylene Terephthalate Glycol (PETG) pellet extrusion (Meibodi et al. 2021). It is observed that PETG deforms due to hydrostatic pressure without stress failure due to its ductile quality with a minimal 10 mm of deformation (Meibodi et al. 2021). The 'Formwork Fabrication Freedom for a Concrete Canoe' project displays state-of-the-art digital fabrication of thin shell PLA formwork. This approach proposes concrete casting, facilitated with progressive sand filling, as a secondary material to control hydrostatic pressure, as thin PLA cannot withstand hydrostatic pressure on its own (Jipa et al. 2019). These methods allow minimal use of material for high resolution formwork fabrication, but their printing and recycling processes consume more energy.
- The 'Reinforced Thin Shell System Formwork for Sandwich Concrete Walls' research demonstrates efficient production, non-standard, cast-in-place, concrete thermoplastic formwork using large-scale AM . By strategically creating fins in reaction to hydrostatic pressure and deformation, the established computational design process in this project improves the formwork's strength in relation to hydrostatic pressure (Meibodi et al. 2022).
- The Eggshell Pavilion, a full-scale, reinforced concrete structure made up of several precast elements, is constructed using FFF 3D printed PIPG (recycled Post-Industrial PET-G) formwork (Burger et al. 2023). The Eggshell Pavilion uses digital casting off, se- on-demand concrete mix, which allows rapid gain in yield strength, preventing the concrete's hydrostatic pressure from causing the formwork's deformation or fracture (Fritschi et al. 2022).

The above-mentioned projects demonstrate computational and fabrication strategies to enhance 3D printed formwork resistance to hydrostatic pressure, offering increased design flexibility, reduced concrete consumption, and minimal material waste.

STATE OF THE ART FOR 3D PRINTING WITH WOOD-BASED MATERIAL

Wood that has been one of the common materials for formwork pre 3DP time, can be a great candidate for 3DP concrete formwork today. Three million tons of sawdust are dumped annually into landfills in the USA alone (Batool et al. 2021). Additive manufacturing using LDM technology for wood-based bio-material provides an opportunity to recycle and reuse 3 million tons of sawdust instead of disposing of it in landfills (Figure 1). Presently, this is practice is contributing to CO2 emissions, as well as releasing toxic waste into the environment.Three-D printed, wood-base material is an emerging area of research.

Three-D printed wood has been intensively investigated, but 3DP wood for concrete formwork application has not. Three-D printed wood has been done mostly through two AM methods: Hot extrusion and cold extrusion (Bierach et al. 2023). Hot extrusion involves heating the material before forcing it out of the printing toolhead; and cold extrusion involves forcing the material out of the toolhead at room temperature. Unlike traditional hot extrusion methods that require high temperatures, cold extrusion allows for the shaping and forming of construction materials at room temperature or slightly elevated temperatures (“3D Printing Bioplastics” 2020). Hot extrusion uses filament which is made of 70% plastic and only 10 to 30% wood. The high temperature level during hot extrusion also poses a risk of burning wood filaments in the process (Das et al. 2021) (Tomec and Kariz 2022). The cold extrusion method of 3DP has gained significant attention in the construction research industry. This technique offers several advantages for the construction sector, including the ability to work with temperature-sensitive materials (i.e. wood that can burn in higher temperatures), and reduced energy consumption. Simultaneously, achieving dimensional accuracy to match the digital twin model presents a challenging task. As a result of these benefits, this research will focus on cold extrusion for newly developed, wood-based material for 3DP. There is growing interest in achieving dimensional accuracy developing biodegradable and recyclable wood-based materials for 3DP. Some major examples are:

- Liquid Deposition Modeling - This is a promising approach for 3D printing of wood (Rosenthal et al. 2017). This research uses a centrifugal mill to ground sawdust on a particle scale to achieve dimensional stability. Grounded sawdust is mixed with a specific binding agent type of cellulose called methylcellulose. This allows material recyclability, as when methylcellulose is re-hydrated, thereby forming a gel-like substancce converting the solid 3D print into its initial paste-like state. These characteristics allow better print resolution due to the grounding process and easy recyclability.
- Wood Warping Composite by 3D Printing (Kam et al. 2022) - This research develops a 100% wood-based biomaterial composite containing wood flour and natural binders, such as cellulose nanocrystals and xyloglucan, without any synthetic resins. Use of natural binders makes it biodegradable and allows easy recyclability.
- 3D-Printed Wood: Programming Hygroscopic Material Transformations (Correa et al. 2015) - This research explores the possibilities of self-transforming geometries using wood FFF filament for 3DP. Wood FDM filaments consist of synthetic binding polymers that are more difficutl to recycle when compared to materials using natural binders. Wood filaments have a better dimensional stability, and they self transform upon moisture exposure causing deformation challenges.

These project spans are mostly on small scales, and involve research in areas such as: in-depth analysis at the particle scale or fiber level, understanding the transformative properties and behaviors of wood-based material, and understanding the printability and dimensional stability in relation to the digital model. The scalability of these projects is challenging, and there is little evidence that utilizing 3DP wood on the construction scale has been done. There is almost no utilization of this application in concrete formwork. .

3DP Wood for Architecture Scale

Only a handful of research projects are focused on achieving scalability of 3DP wood for architecture and construction. In these research projects, wood-based biomaterials are developed to overcome challenges of scalability, deformation, and mechanical strength. However, it represents a small proportion of wood-based content in material mixes with synthetic resins or thermoplastic High Density Poly Ethylene (HDPE) (Opedal et al. 2019). For example:

- ‘Additive Manufacture of Cellulose Based Bio-Material on Architectural Scale (Wei et al. 2021)’. This research explores the application of cellulose, which is a major component of wood and chitosan, in an architectural context through the use of a cold-extrusion setup. The researchers developed a biomaterial, by mixing cellulose and chitosan with the following key ingredients: xanthan gum, which enhances material viscosity, composite homogeneity, dimensional stability and printability; flour and paper fiber, which decreases the dry shrinkage and enhances mechanical strength. As a result, a 1-meter-tall column prototype is made.
- ‘BioHome3D’ is a 600-square-foot prototype house built with wood fiber and bio-resin-based material using FFF 3DP (Dagher 2022). Material formulation combines special-grade biopolymer and pine fibers to optimize printability. Wood fibers are added to enhance the rheology's cooling characteristics, thereby reducing setting time and distortion challenges.
- ‘Wood-based 3D Printing: Potential and Limitation to 3D Print Building Elements with Cellulose and Lignin': This research conceptualizes and develops a novel bio-based and wood-based material. Using LDM AM technology, the researchers succeeded in making 3DP window frames and structural nodes. It was observed, however, that the material lacked mechanical properties comparable to wood, carbon fiber, reinforced polymers, and thermoplastics (Bierach et al. 2023).
- 'Three-Dimensional (3D)-Printed Wood-Starch Composite as Support Material for 3D Concrete

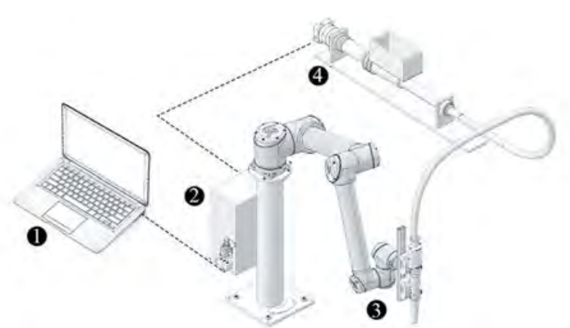
Printing' (Markin et al. 2021, 301). This research develops support material for window, door openings, and overhangs for 3DP concrete structures (Markin et al. 2021, 301). This material exhibits promising mechanical properties and easy recyclability; however, huge fungus formation is observed after 24 hours. Fungus or mold formation in the short term is another challenge that needs to be addressed in biodegradable wood-based materials.

Wood-based materials that are 3D printed with non-biodegradable bio-resins or thermoplastics pose recycling challenges and are less eco-friendly compared to biodegradable wood-based alternatives. It will not enable environmentally friendly construction. Although wood has been a common material for concrete casting, 3D printed wood-based materials have not previously been investigated for concrete formwork. This research focuses on the development of a wood-based 3DP material for concrete formwork that is scalable, easily recyclable, biodegradable, and mold free.

METHOD

Robotic Simultaneous 3D Printing and Casting Set-on-Demand Concrete

This research expands the state-of-the-art AM LDM method for reinforced concrete formwork, by developing a digital fabrication and material development approach, to enable Robotic 3DP (Figure 2) of concrete formwork from a fully recyclable and biodegradable wood-based material. The new, wood based material compositions are first tested for printability using various biopolymers, solvents and additives. The material research is conducted at three different scales, micro, meso and macro. The final chosen material is then 3D printed and sequentially casted with concrete, simultaneously. The sequential casting of set-on-demand concrete is necessary to overcome the challenge of scalability and hydrostatic pressure.



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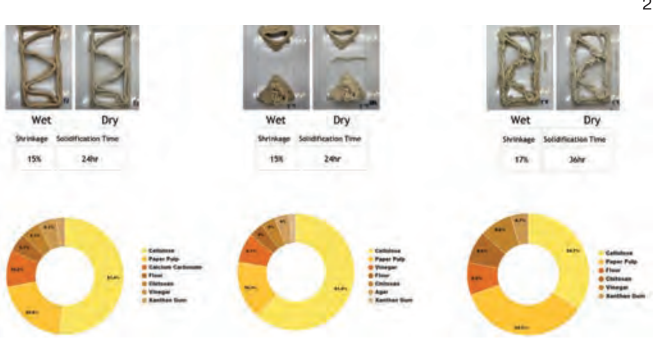

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2 Fabrication set-up. (1) Computer, (2) Beckhoff PLC controller, (3) UR Robotic arm with 1.5"inch tube and 11mm PLA nozzle, (4) PC Pump.

3 Examples of material samples extruded using syringes and their composition.

Selection of Material and Material Research

This research aimed to create a new wood-based material suitable for 3DP freeform formwork, ensuring its printability, 100% recyclability, and biodegradability. The material used in this method comprises three distinct categories of ingredients: bio-polymers, additives, and solvents. Biopolymers are polymers produced from natural sources as they are derived from living organisms like plants and microbes. They play a crucial role in binding all the ingredients together, and they are a renewable resource, unlike other petroleum-based polymers. Additives serve as core ingredients responsible for enhancing strength, facilitating setting time, and regulating moisture content. Solvents aid binding and optimizing material viscosity, making a paste-like texture. This research uses chitosan, flour, and xanthan gum as biopolymers; sawdust, cellulose, paper pulp, magnesium oxide, calcium chloride, and calcium carbonate as additives; and water and vinegar as solvents.

To achieve the optimal viscosity of the material, the two crucial aspects to look at were stability and extrudability. We, therefore, conducted a series of 20 tests (Figure 3) using a manual syringe extrusion technique. These tests involved experimenting with different compositions of above-mentioned ingredients. Increased amounts of strengthening additive raise the viscosity, hindering material extrudability. It is essential to find the perfect balance between the two. The objective is to have a material with optimum strength and viscosity, as it directly affects 3D print speed and buildability. After evaluating, we determined that a final material composition consisting of 42.5% sawdust and 13.9% paper pulp provided the best results, in terms of meeting the criteria of buildability, printability and extrudability. Observing the setting time is vital because a quicker setting time leads to faster solidification and faster 3D print speeds, ultimately enhancing the strength of the 3DP formwork.

Material Preparation

This research introduces a four-stage method for wood-based biomaterial preparation for robotic 3DP. The first

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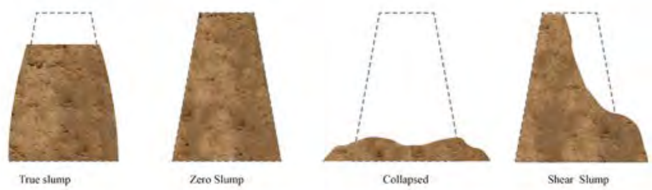

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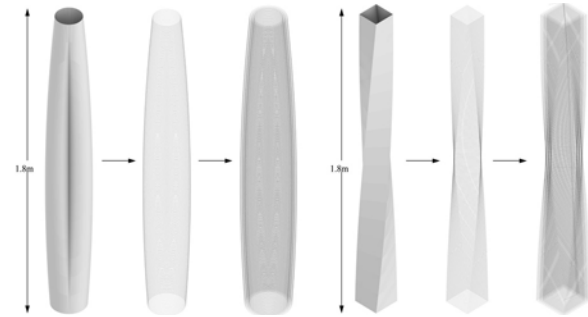

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4 Preparation of sawdust powder using electric grain grinder mill.

5 Material slump test.

6 Toolpath generation of Column 1 (right) and Column 2 (left).

7 Image showing the casted column and 2-inch formwork..

stage is to grind sawdust (millimeter to sub-millimeter size). A size reduction from macro- to meso- to microscale is needed for dimensional stability (Figure 4). The second stage begins once the sawdust is fine enough in particle size. For dimensional stability and compressive strength, 42.5% sawdust is mixed with 13.9% paper pulp, 9.3% cellulose and 4.7% calcium carbonate, allowing wood-based formwork the strength to withstand hydrostatic pressure. To make the material mold proof, 11.6% magnesium oxides are added. To bind additives and increase material viscosity, binding agents like 4.7% flour, 4.7% xanthan gum and 4.7% chitosan are added to the dry mix. To activate the binding agents and make it into a paste, solvents such as water and vinegar are added to the mix. Water (3.5L) is added to the dry mix at room temperature activating xanthan and flours sticky binding properties to bind all the components together (Chaturvedi et al. 2021) .. Binding agents also aid in 3D printed layers' adhesion to one another. To decrease the settling time of the mixture, 61 grams of calcium chloride are added. A commercial mixer is used to mix the material until a paste is formed.

Material Printability

Once the paste is prepared, meso research centers on examining the printability of the previously mixed material. A slump test is conducted for the developed material (Figure 5). If a true slump is recorded, then the wood-based biomaterial indicates minimal self load buckling, which means the material has optimum printability and pumpability. The third stage is to feed this homogeneous mixture in the pump and start extrusion according to the desired morphology of formwork to provide minimal print deformation.

1:1 Scale Prototyping: Pumpability, Printability, and Buildability

To examine and evaluate the research method and material matrix, column prototypes up to 1.80m tall have been designed and fabricated. The prototype investigated the 3DP of wood formwork and simultaneous sequential rebar integration and concrete casting, to examine and demonstrate this concept.

Simultaneous 3D Printing Formwork Fabrication and Sequential Casting

The last stage is to initiate Robotic 3DP of the formwork, and to start sequential set-on-demand concrete casting after every six inches of the completed print. Concrete is poured after six inches to avoid hydrostatic pressure which would deform the 3D printed formwork. Formwork printing utilizes Grasshopper computer software scripts to model a tool path (Figure 6) with minimal overhangs for the Universal Robot. Overhangs lead to deformation and material collapse, influenced by rheology and setting time. The resulting G-code (geometric code) is uploaded to Universal Robots firmware. Two experiments utilizing 1-inch and 1.5-inch formwork with a ranging diameter of six to eight inches were carried out, both exhibiting deformation and fractures when subjected to hydrostatic pressure.

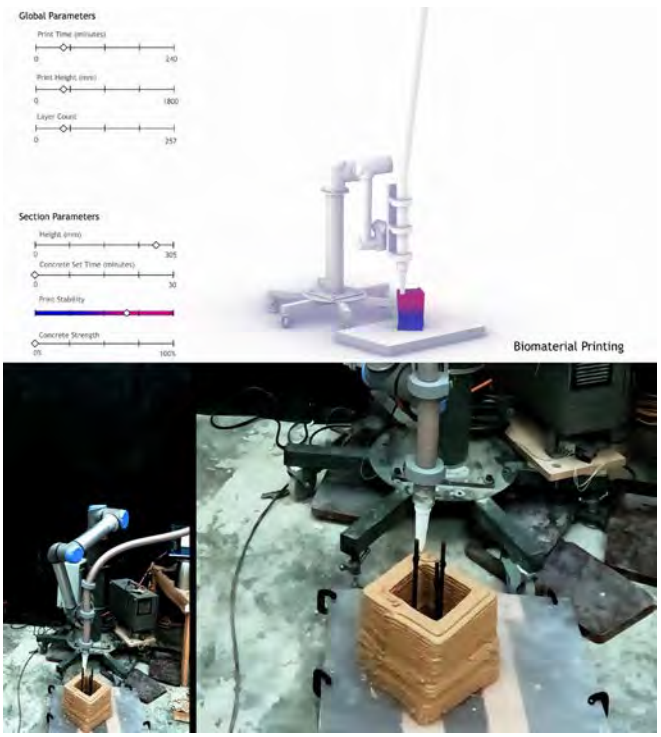
When using 2-inch formwork, hydrostatic pressure was resisted with less deformation (Figure 7) when printed for a freeform column. Therefore, the optimum ratio of formwork thickness with the larger diameter is 1:4.

Concrete Mix in Relation to 3D Printed Formwork

The proportion and consistency of the concrete mix is very crucial in order to keep the formwork from cracking due to hydrostatic pressure. Two kinds of off-the-shelf concrete mixes were used in batches of 10 lbs (5 lbs each), with both of them have their own accelerators added to them. One of them has coarse aggregate and a setting time of 15 minutes; the other has fine aggregate and a setting time of 20 mins. A 15-minute period of time was too short, causing cold joints to form; whereas, 20 minutes were too long. Therefore they were mixed together with 2 liters of water, creating a slurry paste-like consistency, and each batch was cast with rebars in 10-minute intervals to maintain the bonding between each batch, thereby preventing cold joints and hydrostatic failure (Figures 8 and 9).

Recycle and Reusability Process

After simultaneous 3DP and sequential set-on-demand casting is complete, woodbased formwork is removed after a period of three hours. When removed, the material is in a semi moist condition containing 50-60% moisture. At this point in time, the wood-based material is rehydrated with fresh water. The biopolymers (chitosan, flour, and xanthan gum) are reactivated by hydration during the recycling process.Reprinting entire recycled formwork is not challenging, for physical or chemical reasons; however,



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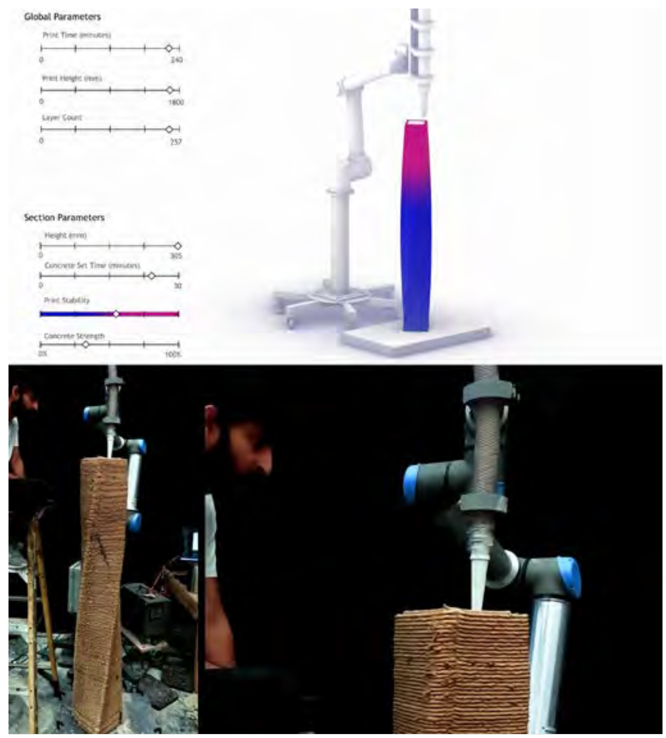

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8 Simultaneous 3D printing and sequential casting with rebar integration at 1ft.

9 Simultaneous 3DP and sequential casting with rebar integration at 6ft.

10 Recycling process.

11 Images of sample before disintegration and degradation.

12 Image of sample after 5 months of disintegration and degradation.

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	Column 1	Column 2
Print Time *(hrs)*	6	4
Print Speed *(mm/s)*	14.7	36.5
Mass of wood based Material *(lb)*	52.9	70.5
Mass of Concrete *(lb)*	250	206.5
Concrete Set Time *(hrs)*	6.5	4.5
Overhang Angle *(deg)*	1.4 - 4.2	4.5
Mean Cloud-to-Mesh Distance (mm)	8.25	7.08
Rebar Integration	No	Yes

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13 Photogrammetry Scan of Column 1 (left) and Column 2 (right).

14 Printing comparison data.

15 Column 1 Cloud-to-Mesh Distance.

16 Column 1 Cloud-to-Mesh Distance.

17 Column 2 Cloud-to-Mesh Distance.

18 Column 2 Cloud-to-Mesh Distance.

19 Column 2 with formwork intact.

20 Column 2 with formwork partially retained.

in the long term, the formwork dries, gaining complete compressive strength, becoming harder and more difficult to rehydrate. Therefore, the dried formwork is ground into millimeter to sub-millimeter size and then rehydrated (Figure 10). Once the mixture reaches the same viscosity as before, it is ready for 3DP. Material is reused, recycled, and printed 25 times without any obvious deficiency in the quality of layer adhesion in the 3D printed formwork.

Biodegradability

In order to study the biodegradation of the material, a sample (36” x 6” x 6”) was left outside for five months, from December to April. The sample (Figure 11 and 12) has sustained two snowstorms, extreme heat, and heavy rainfall. Water and moisture contribute to material rehydration, causing erosion and facilitating fungal growth, leading to biodegradation.

Geometric Analysis for Deformation between Digital and 3D print

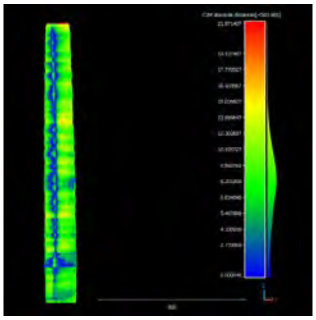
Three-dimensional digital scans of the columns were created for geometric analysis using photogrammetry (Figure 13). Scanned meshes were compared to 3D models using CloudCompare. Point clouds (100,000+ points) were extracted from scans and used to calculate Mean Cloud-to-Mesh Distances for each column. This was done to observe dimensional accuracy with the digital twin model.

RESULTS AND DISCUSSION

The method described in the previous section was applied in the fabrication of two 1.8-meter-tall, sequentially cast, concrete columns. The wood-based material used was 3DP and recycled 25 times before being employed for the columns. The post-processing phase involved manually removing the wood-based material, resulting in salvaging 97% of the material for reuse and 3% wastage. Wet concrete's fragile bonding with 3D printed wood-based material hampers recycling due to contamination. High-pressure water removes residual bonded material from the concrete column surface. A comparison of the printing parameters and material usage of the two columns is shown in Figure14.

Column 1 (C1) was 3DP in 6 hours at a speed of 14.7 mm/s using 52.9 lbs of wood-based material and 250 lbs of concrete, which was set in 6.5 hours. It had an organic design with a variable overhang angle (1.4 to 4.19 degrees). The mean Cloud-to-Mesh distance (Figures 15 and 16) was 8.25 mm, with a standard deviation of 6.05 mm and a maximum distance of 21.87 mm.

Column 2 (C2) was 3DP in 4 hours at a print speed of 36.5 mm/s using 70.5 lbs of wood-based material and 206.5 lbs of concrete, which was set in 4.5 hours. It incorporated twenty-one 1-foot rebar segments tied in groups of three, spaced 3" apart, to strengthen the joints. The design had a constant overhang angle of 4.48 degrees. The mean Cloud-to-Mesh distance (Figure 17 and 18) was 7.08 mm, with a standard deviation of 4.25 mm and a maximum distance of 25 mm.



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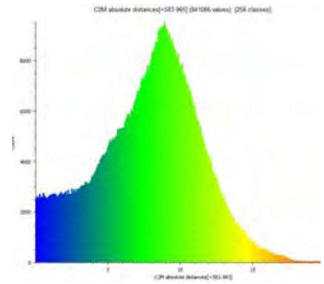

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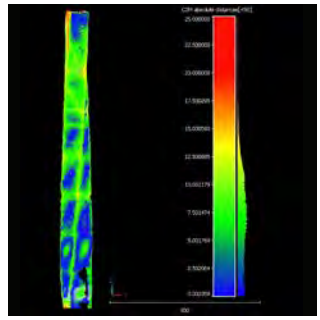

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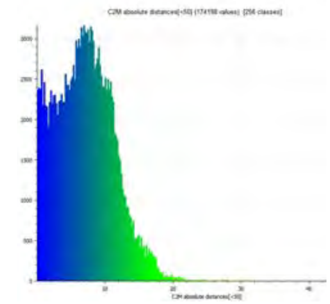

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Comparing the two columns, there was a notable improvement in terms of print speed and dimensional accuracy in C2 compared to C1. The fast setting time of concrete, leading to improved dimensional accuracy, indicates that additional testing and refinement in the fabrication process could yield even better results.

The surface finish of the cast columns exhibits textured ridges that result from the concrete flowing into the gaps between the layers of the wood-based material formwork (Figure 17). This distinctive appearance, resembling a fingerprint, is a characteristic of the fabrication process. Unlike concrete cast into 3DP thermoplastic formworks, which typically have a smooth finish due to the small layer height, the concrete forms produced using this technique have a unique and organic appearance. The slight deviations and imperfections in the banding add to the overall organic aesthetic of the final product, setting it apart from the smooth and flawless appearance commonly associated with digital fabrication and computational design.

CONCLUSION

The aim of 'BioMatters' research was to create and explore the potential of a new recyclable wood-based biomaterial. By scavenging leftover sawdust, we were able to upcycle it for 3DP concrete formwork on an architectural scale. By doing so, there's an opportunity to salvage 3 million tons of sawdust that is either dumped in US landfills annually or burned (causing air pollution). Large quantities in landfills can be harmful due to the release of lignin and fatty acids during decomposition, posing risks to water supplies and wildlife.

However, wood-based biomaterial 3DP requires a simultaneous set-on-demand, sequential casting method to overcome hydrostatic pressure. This becomes a time-sensitive process that requires quality manpower to develop wood-based material and concrete mix during 3DP. Wood-based biomaterial needs to be improved for better resolution, dimensional stability, and fast setting time for non-planar geometries with greater overhangs. Further research is needed to determine a more efficient

21 Tests and final columns.

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fabrication method, and to optimize the design-to-fabrication workflow.

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