EXTRUDING DREDGED-BASED MATERIAL FOR CONCRETE FORMWORK THROUGH RAPID LIQUID PRINTING

TZU-HSIEN LO[1] and BOSHENG LIU[2]
[1,2]Feng Chia University.
1lozixianschool@gmail.com, 0009-0005-1669-0303
[2]bsliu@fcu.edu.tw, 0000-0001-7288-9230

Abstract. The research delves into investigating the printed reusable Dredged-Based Material (DBM) concrete formwork using Rapid Liquid Printing (RLP) technology, revealing its potential impact on existing concrete construction by substituting sacrificial formwork usage. This is an initial exploration of the Rapid Liquid Printing process injecting Dredged-Based-Material material (M1) into the water environment (M2), where the water acts as the suspension and phase-changing accelerator. The Dredged-Based Material injection involves meticulously blended dredged material with bio-based cetyl palmitate. This paper focuses on designing and implementing an extrusion system and the extruder head utilizing stepper motors to control the flow rate, ensuring a stable extrusion state while monitoring the temperature. The Dredged-Based Material for the Rapid Liquid Printing experiment uncovered the challenge and the solution of creating a consistent extrusion through a custom extruder that can maintain the Dredged-Based-Material workability and construct a proportionally scaled prototype to validate the findings and practicality for the Dredged-Based Material Rapid Liquid Printing approach.

Keywords. Rapid Liquid Printing, Dredged-Based Material, Reusable Material, 3D Printed Formwork, Reusable Concrete Formwork

1. Introduction

In architecture and building construction, researchers and designers have identified additive manufacturing (AM, also known as 3D printing) as a potential solution that uses less material to manufacture the final product while satisfying overall design and structural requirements at various scales and opportunities. Specifically, the technology of 3D Concrete Printing (3DCP) (Gosselin et al., 2016) using Fused Deposition Modeling (FDM) (Masood, S.H., 2014) has become one of the most common applications in the construction industry. This technique allows the precise construction of structures by depositing freshly mixed concrete at specific locations. However, 3DCP faces several challenges (Panda et al., 2018), such as the accuracy of the outcomes heavily depending on the performance of the extruder, the inability to print cantilever structures without support, challenges in adding vertical reinforcement, and the presence of anisotropic properties in the printed objects. Most research directions

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in concrete 3D printing have been concentrated on three main methods: material extrusion, powder bed binding, and material jetting (Hack, N., et al., 2020). A variation of the 3DCP method (Li, C., et al., 2021; Hack, N., et al., 2020), utilizing Rapid Liquid Printing (RLP) (Hajash, K., et al., 2017) to develop the Injection 3D Concrete Printing (I3DCP) process. This method is based on robotically injecting a fluid material (M1) into a medium with specific rheological properties (M2), enabling the material M1 to maintain a stable position within M2. Unlike horizontal layer-by-layer deposition, this approach allows for creating complex concrete structures through freeform trajectories in space.

Dredged material (DM) is an abundant natural resource that often contains large amounts of clay, silt, sand, and organic matter. The study discovered that mixing the DM with non-petroleum-based hydrogenated glycerides (HG, an essential compound in wax) and printing in water at room temperature results in an instant phase-changing effect from liquid to solid. The mixed liquid DM material here is referred to as Dredged-Based-Material, DBM, in this research paper. This research uses the experimental trial and error method, a problem-solving strategy characterized by repeated, varied attempts until a successful outcome is obtained. From the initial stages of material testing to the current phase of extruder testing, we have used this research methodology to better integrate DBM with the RLP manufacturing method to create reusable sacrificial concrete formwork. Regulating the DBM properties and the M2 environment allows the M1 to print along free trajectories in space. Unconstrained by the limitations of traditional 3D printing, it offers higher manufacturability and greater design freedom. Moreover, the characteristics of this material allow for a rapid printing process, presenting a highly potential and scalable manufacturing method for the construction industry.

2. Material Design

2.1. PRINTING CHARACTERISTICS

3D printing in building construction, particularly concerning the application of printing material's mechanical properties, includes three critical, pivotal material attributes: Extrudability, Workability, and Buildability (Li, Z., et al., 2020; Liu, B. and Liu, R., 2019; 2021). These attributes are essential in determining the accuracy and predictability of the 3D printing process. In addition, one attribute is equally essential: the extrusion system capability. These four attributes uniquely impact the 3D printing process and interact with each other. This research examines the DBM's extrudability, workability, and buildability using a 0.5 HP DC motor (EHP 281-SSIPUMP-TW) in the RLP process while utilizing water (M2) as an accelerator agent.

The M1 material is DM mixed with hydrogenated glyceride materials at 60°C, a non-petroleum-based material. The newly mixed material undergoes a phase change from liquid to solid under temperature changes in the M2 environment. Compression tests were conducted to examine the hydrogenated glyceride and the DM mixture ratios and their impact on the solid phase strength of the mixtures. The extrudability and workability mixtures are 40% binding agent and 60% silt DM (i.e., 40%/60%), 35% binding agent and 65% silt DM (i.e., 35%/65%), and 30% binding agent and 70% silt

DM (i.e., 30%/70%). Each mixture was cast into a 1:2 tall ratio cylinder to create 30 test samples. Each mixture was randomly selected 10 samples from each batch of 30 and tested using a compression penetrometer ranging from 0 to 5 MN/m² (MPa) (Figure 1). The results showed that the 40%/60% mixture could withstand an average pressure of 57.3 kPa, and both the 35%/65% and the 30%/70% mixture could endure 63.7 kPa without failure (Liu, B., et al., 2023). Due to the glutinous level, a DM percentage of 30%/70% or higher is unworkable and not extrudable. Therefore, the final chosen ratio was 35%/65%.

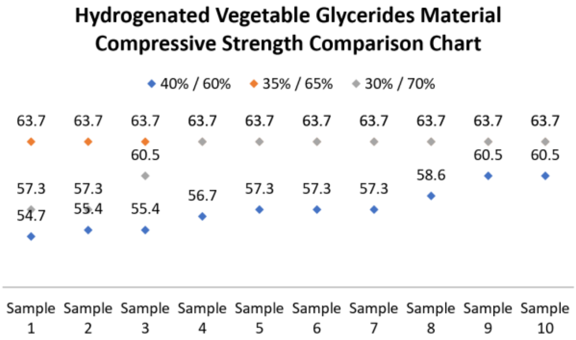

Figure 1. M1 material mixture proportion and compression strength

2.2. RLP PROCESS (M1+M2)

The research investigates hydrogenated glyceride material as the binding agent with the DM (M1), referred to as DBM. The DBM was injected into room temperature water (M2) to 3D print (RLP) concrete formwork techniques. Using a 0.5 HP DC motor as a pump, the experiment creates an infinity feeding system to push the M1 material into the extruder (Figure 2). The printing process is supported by an electromechanical control system comprised of stepper motors and screws to maintain the stability of the printing operation. This system ensures consistent movement and flow of the material, contributing to the precision and reliability of the printing process. Due to the phase-changing of the M1 material, a reheating system is designed in the extruder to prevent the system from potentially clogging.

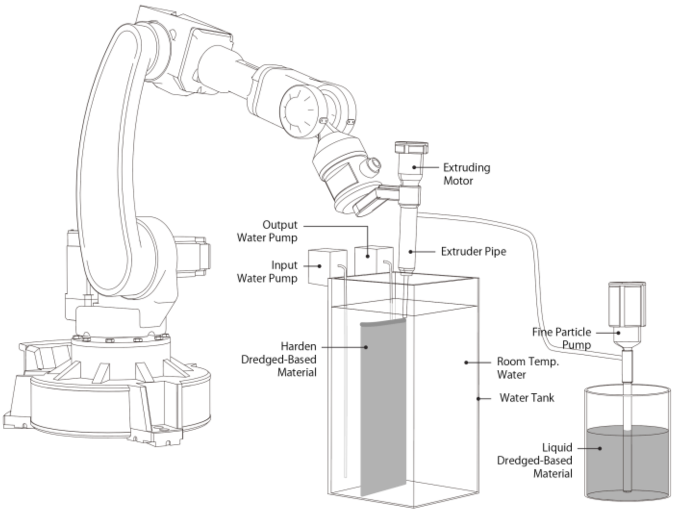

Figure 2. Injection printing setup diagram

3. System of Printing Process

3.1. EXTRUDER DESIGN

Extruder design plays an essential role in this DBM RLP process because part of the extruder requires re-heating M1 material, and the chamber needs to relieve excessive pressure from the pump's printing speed (11.34 cm^3/s). As a result, several materials, including copper, aluminum, GFP, and glass, were studied to find the proper thermal conductor that would not transmit electricity for safety reasons. Ultimately, glass material was selected and applied to the nozzle for its good thermal conductivity and non-electricity conducting properties.

In the early stages of extruder experimentation, it relied solely on the pump's adjustable voltage controller to regulate the amount of M1 material from the nozzle (11.34 cm^3/s) with no pressure release valve. As a result, the DBM RLP speed is uncontrollable. The following iterated extruders incorporated a NEMA 23 motor and dynamic thread width screw mechanism, allowing more precise control during the injection process (Figure 3). Due to the internal chamber design, the screw pitch was set at 10 millimeters to ensure its extrudability. Considering the M1 temperature constraints, an insulated connection between the screw and the motor was deployed. As a result, a pressure release point was formed between the extrusion chamber and the motor.

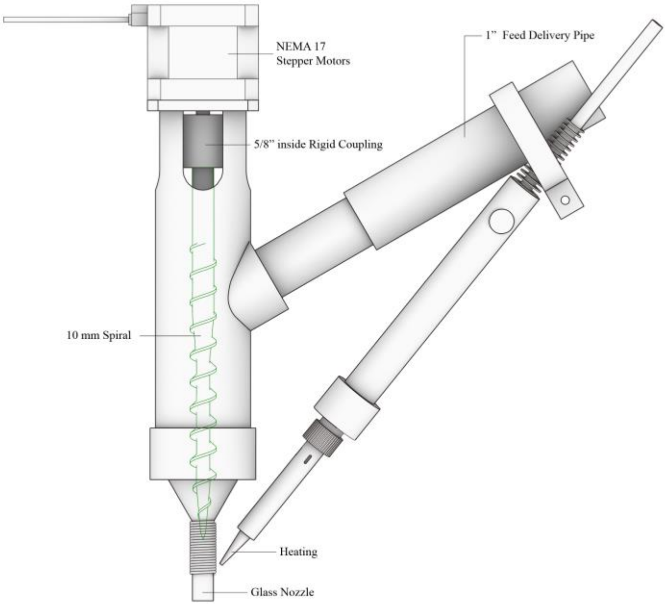

Figure 3. Extruder

During the extruders' testing processes, it was found that the location of M1 entering the extrusion chamber and its diameter would significantly impact the inject-printing results. The final chamber design considers the pump volume per second (11.34 cm³/s) times 16 seconds of material extrusion pressure delay, then times 1.5 safety factor. Furthermore, the chamber of M1 needs to take 24 seconds of extrusion volume (a volume of 273.38 cm³). This volume ensures sufficient space for the material to reside within the chamber with a pressure release valve at the top. Based on these findings, the next step is to make the corresponding adjustments to improve the efficiency of the DBM RLP injection process.

3.2. WATER TANK (M2)

The M1 is injected into the M2 environment, the total size of M2 is 25.4 cm x 43.9 cm x 26 cm (Figure 4). An important discovery was made during the initial RLP process. When the volume of M2 was filled with water, M1 (50%/50%) would levitate. This result indicates that the M1 density was less than 1 g/cm³. In this condition, water can support the M1, which is still within the principle of RLP. Finally, a gradual water-feeding system was utilized during printing to avoid the high levitate effect and the volumetric water pressure. In this case, inject-printing a layer 90 mm diameter cylinder with 6 mm thickness and 3 mm height requires 330 ml of water added prior to the printing, thus ensuring the stability of experimental conditions.

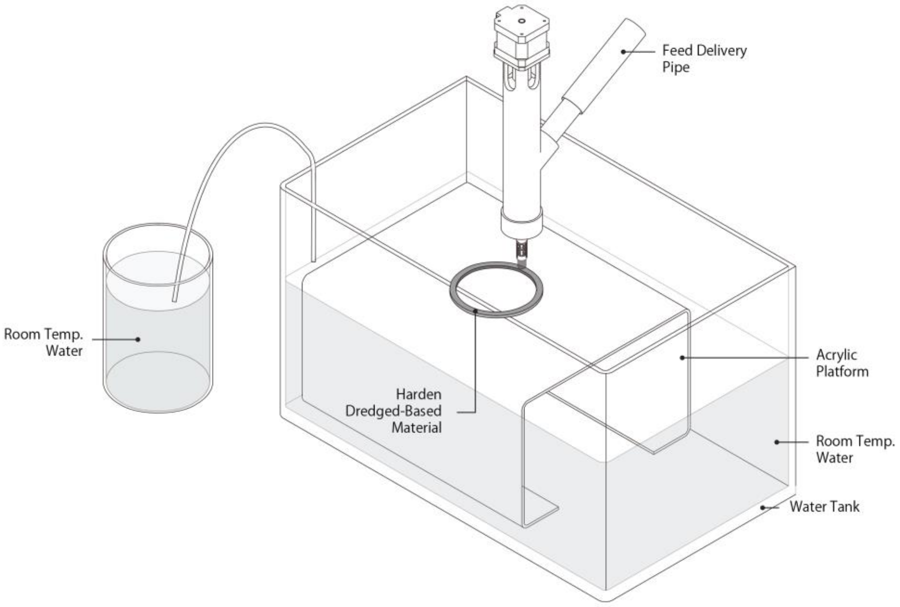

Figure 4. Water tank system

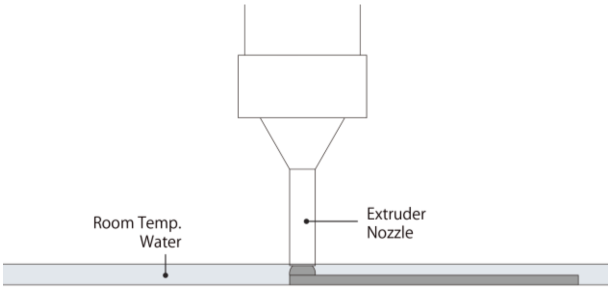

Figure 5. Injection in water

4. Printing Result

The present paper discusses an initial investigation into DBM RLP technology. It mainly emphasizes the interaction between the M1 material and M2 water fluid through a series of tests. Based on the formula for density (D=M/V), the current DBM M1 mixture (35%/65%) has a density of 1.31 g/cm³. Although the inject-printed M1 currently has no water buoyancy support, M2 still acts as the accelerator for the M1 to phase-change from liquid to solid. As M1 material has the strength to keep itself in place, injecting a cantilever is still possible. However, changing M2 density to a higher-density liquid is under investigation. In the injection-printing process, the speed of the M1 injection, the steady addition of water, and the synchronous increase in printing layers were crucial, ensuring the solid adhesion of the material and preventing layer separation due to the M1 material phase-changing too quickly, which is exhibited in Figure 6.

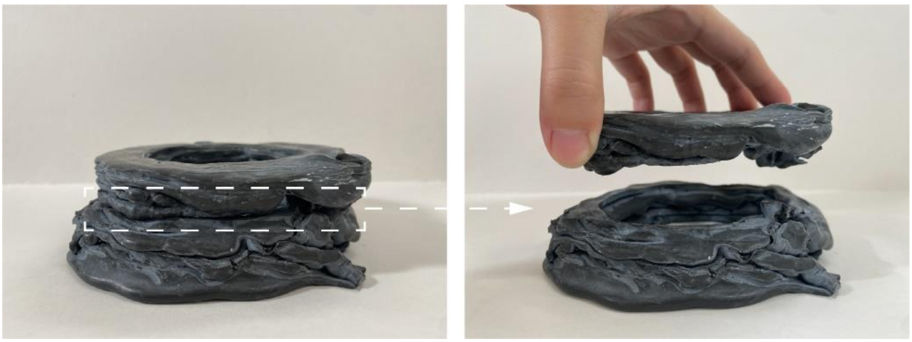

Figure 6. Injection printing result

This research serves as a proof of concept and showcases the potential of the DBM RLP technology. However, several challenges and unknown factors require further investigation. Firstly, it is essential to identify the formula for the M1 chamber and its maximum extrusion rate to prevent overflow during extrusion. Secondly, a method for automatically incrementally increasing M2 volume is needed to prevent layer separation. Thirdly, there must be systematic monitoring of the temperature of M1 during the extrusion process to ensure that external factors do not reduce the temperature, leading to premature cooling and solidification. Lastly, a more precise printing control mechanism is required, including installing the extruder on a robotic arm or multi-axis machining equipment to ensure stable, uniform, and efficient extrusion. It is important to emphasize that the success of DBM RLP technology relies on analyzing extrudability, workability, and buildability with manufacturing processes and material parameters. These elements cannot be viewed in isolation. Therefore, to progress in research, coordinated efforts must be made between material design, structural design, and manufacturing processes.

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