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Overview of Injection Liquid Printing with Dredged-Based Material for Concrete Formwork

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Abstract

This research examines the integration of dredged-based materials with injection printing for creating recyclable concrete formwork. It demonstrates how this innovative additive manufacturing (AM) method can significantly enhance reinforced concrete construction by reducing the use of sacrificial materials and formwork. This process employs a mix of dredged material and non-petroleum-based hydrogenated glycerides—a crucial wax formulation component—within a water-based environment. The material's buildability, extrudability, workability, and predictability were evaluated through unconfined compression tests. The research focuses on refining the rheological properties of the materials to ensure their effectiveness in the injection printing process. A specially designed extruder was developed to ensure consistent and predictable material extrusion, critical for the structural integrity of the formwork. This research has produced scaled prototypes to further validate the approach. By merging innovative materials with advanced manufacturing techniques, this study promotes a sustainable construction model, highlighting the intricate relationship between material properties, extrusion design, system control, and temperature management. It opens new avenues for fabrication and constructability in the realm of recyclable concrete formwork, representing a significant advancement in sustainable construction practices.

Keywords: Dredged-Based Material, Reusable Material, 3D Printed Formwork, Reusable Concrete Formwork, Injection Printing

1. Introduction

In recent years, the introduction of 3D printing technologies has marked a significant shift in the landscape of manufacturing and construction, propelling these industries into a new era characterized by an unparalleled level of design flexibility and material innovation. Among the spectrum of additive manufacturing (AM) techniques [1], Rapid Liquid Printing (RLP) [2] [3] and Injection 3D Concrete Printing (I3DCP) [4] [5] have emerged as pioneering approaches, redefining the boundaries of concrete application—a material traditionally constrained by its formability and customization options.

RLP offers a groundbreaking method that transcends the limitations of traditional horizontal layer-by-layer manufacturing by employing a gel-like suspension medium. Conceptualized by Hajash and Kathleen in 2017, this approach facilitates the freeform production of objects. It involves injecting a curable material into the medium to achieve complex geometries swiftly and accurately, eliminating the need for additional support structures. The versatility of RLP to accommodate diverse materials, including concrete, heralds new horizons for architectural and structural design, meeting the growing demand for intricate and tailor-made solutions. The RLP system revolutionizes 3D printing by integrating rapid curing materials and a supportive granular gel medium, substantially enhancing manufacturing speed. This rapid curing is particularly advantageous over traditional methods, which often suffer from prolonged curing times that complicate sequential layering and bonding processes. Additionally, the RLP system employs a unique granular gel as a suspension medium, maintaining the printed material in a quasi-fluid state for enhanced nozzle mobility and structural integrity. This dual functionality positions the RLP system as a transformative approach in 3D printing technology. Despite these advancements, current research such as 'Printed silicone pneumatic actuators for soft robotics' [6] demonstrates that the scale of achievements using RLP in soft robotics still faces significant limitations (Figure 1). The study showcases the use of RLP to improve the performance and manufacturability of silicone pneumatic actuators, but its application scope remains constrained within relatively modest scales and complexity levels.

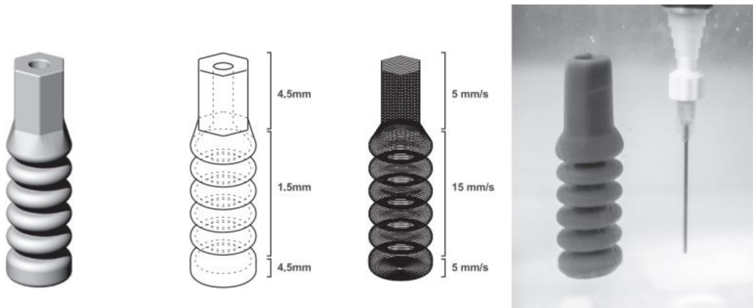

Figure 1: RLP Process A. CAD Modeling B. Sectioning C. Toolpath Generation D. Printed Actuator [https://doi.org/10.1016/j.addma.2021.101860.]

Parallelly, Injection 3D Concrete Printing (I3DCP) was introduced after RLP, introduces an innovative approach to constructing concrete structures by injecting a fluid concrete mixture into a secondary material with specific rheological properties, as detailed by Hack and colleagues in 2020 . This method enables the fabrication of spatially complex structures that challenge conventional manufacturing and construction methods, offering a leap towards multidimensional printing devoid of gravity and layering limitations. Specifically, I3DCP manifests in three innovative modalities: Concrete in Suspension (CiS), Suspension in Concrete (SiC), and Concrete in Concrete (CiC). The advent of I3DCP signals a pivotal transformation in construction methodologies, envisioning a future where architectural creativity is not hampered by the existing constraints of concrete forming. However, the application of AM technologies, particularly Fused Deposition Modeling (FDM), within the building construction sectors highlights several challenges. The precision of 3D Concrete Printing (3DCP) outcomes is heavily dependent on the machinery employed, and limitations such as the inability to print overhangs, difficulties in adding vertical structural reinforcements, anisotropic structural performance, and the necessity for post-processing due to layer stacking are prevalent. Moreover, the I3DCP method, while offering solutions to anisotropic characteristics and enabling the creation of overhang forms, faces challenges in geometric precision, material overlay uncertainty, and the predictability of concrete creep and shrinkage. This paper seeks to offer an alternative perspective to the traditional and novel 3DCP challenges by leveraging the RLP method with custom-mixed dredged material for enhancing concrete construction processes.

In 2023, our research team presented at the International Association for Shell and Spatial Structures (IASS) Annual Symposium on the application of Liquid Printing technology in producing recyclable concrete formwork. Innovative 3D printing technologies in construction leverage the properties of dredged material (DM), a resource rich in clay, silt, sand, and organic matter. Recent studies have focused on the development of Dredged-Based Material (DBM) by mixing DM with non-petroleum-based hydrogenated glycerides (HG), a key component in wax. This mixture undergoes an instantaneous phase change from liquid to solid when printed in water at room temperature, using water as an accelerator agent in the RLP process. This phase-changing behavior is critical for the material's extrudability, workability, and buildability, attributes that determine the precision and reliability of 3D printing in construction [7] [8] [9]. The research employs a trial and error methodology to optimize these properties by adjusting the DM and HG ratios and testing these mixtures under varying conditions. For example, mixtures of 40% HG to 60% silt DM, 35% HG to 65% silt DM, and 30% HG to 70% silt DM were examined, with the 35%/65% ratio ultimately providing the best balance of extrudability and workability, enduring up to 63.7 kPa in compression tests (Figure 2) [10] [11].

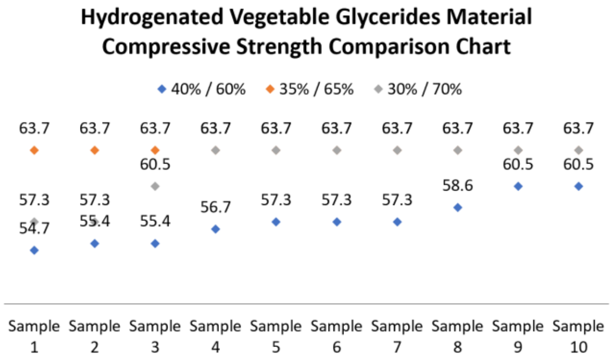

Figure 2: M1 material mixture proportion and compression strength

To demonstrate the recyclability of the material, compression strength tests were using the MTS 810 servo-hydraulic testing machine, following CNS 1010 standards. The test specimens were 50mm cubes, including DBM without contact with concrete (Figure 3) and DBM mixed after contact with concrete (Figure 4). The calculations revealed that the average compressive strength of the DBM without contact concrete was 5.93 kgf/cm², while the average compressive strength after contact concrete was 6.51 kgf/cm². This indicates that the DBM exhibits higher compressive strength after contact with concrete. The purpose of this experiment is to demonstrate the lateral pressure that the material can withstand when used as a mold. During the casting process, the pressure of fresh concrete is referred to as lateral pressure, which increases with the height and rate of concrete placement. Calculating the pressure on the mold is crucial to prevent any structural issues. The formula for calculating the concrete pressure on the formwork is P =hC/A, where P is the pressure in kN/m², h is the concrete height in meters, C is the unit weight of concrete in kN/m³, and A is the contact area of the formwork in m². It is noteworthy that the pressure exerted by the concrete on the formwork is often proportional to the height of the formwork. In Taiwan, the Japanese architectural standard JASS5 is commonly used for calculations. In this research, the unit weight of concrete is approximated as 2400 kgf/m³. Assuming a vertical retaining wall with a height of 2 meters, the lateral pressure exerted by the concrete on the formwork is calculated to be 0.48 kgf/cm². By integrating the data, it is determined that the dredged material can withstand a maximum height of 24.63 meters per cubic unit.

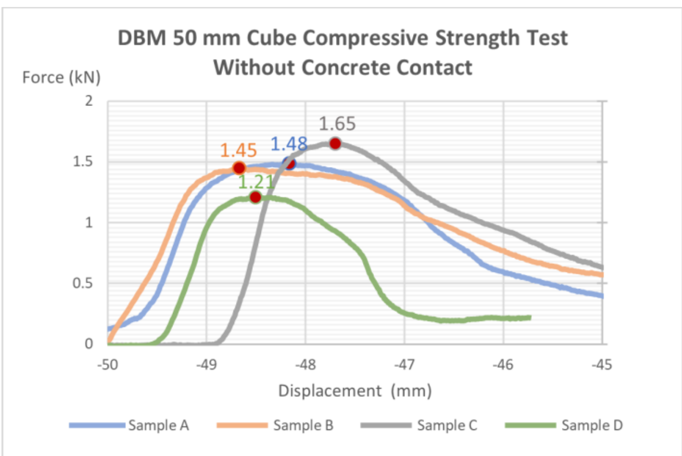

Figure 3: DBM 50 mm cube compressive strength test without concrete contact

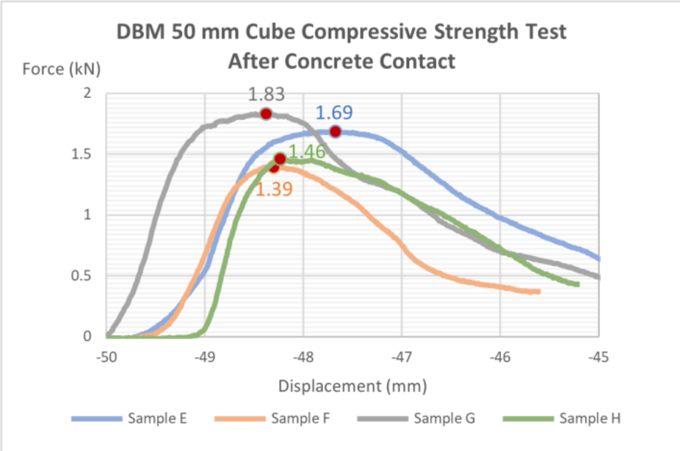

Figure 4: DBM 50 mm cube compressive strength test after concrete contact

2. DBM printing process

2.1. Relationship of Material 1 and Material 2

In the research, the utilization of hydrogenated glyceride as a binder, designated DM (M1), for 3D printing concrete formworks was explored by introducing it into a room temperature water environment (M2). The printing process is characterized by injection printing rather than printing in a suspension rheology. When M2 is completely filled, the volumetric pressure of M2 sufficiently impacts the first layer of M1 within the tank, occasionally leading to inconsistent pressure build-up and uneven extrusion (see Figure 5), which may cause detachment from the base. However, as the volume of M2 increases with the layer height of M1, buildability is enhanced, enabling the printing of structures with overhangs and cantilevers. Additionally, when M1 briefly contacts M2, the material remains workable before it completely hardens. The rapid hardening speed and phase change properties of the M1 material align closely with the principles of RLP, enhancing the versatility and reliability of the printing process. In the printing system, a stable printing process is achieved by controlling the flow and pressure of the M1 material from the extrusion chamber to the nozzle.

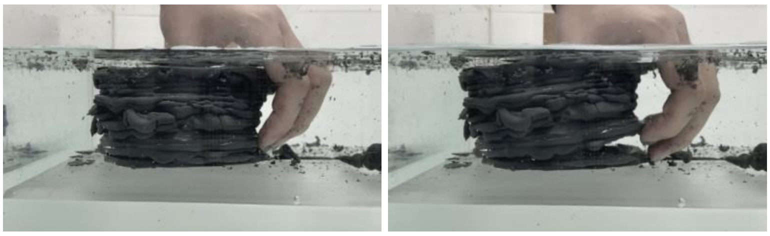

Figure 5: Water environment leads to seperate

2.2. Material 2 Set up

The research explores DBM injection printing technology, particularly focusing on the interaction between M1 material and M2 water fluid within a defined space measuring 19.9 cm x 30.3 cm x 22 cm (Figure 6 (a)). Initially, the M1 material mixture, comprising 35% M1 and 65% water, demonstrates a density of 1.31 g/cm³, exceeding the density of water (1 g/cm³), which results in M1 sedimentation rather than suspension when injected into the fully water-filled M2 environment. This finding underscores that M1 which cannot float on water, consistent with I3DCP principles and highlighting M1's rapid hardening, crucial for RLP. To manage the effects of volumetric water pressure and facilitate the rapid phase change of M1 from liquid to solid, a gradual water-feeding system was integrated, allowing for the steady addition of water during the printing process. This setup ensures the material's solid adhesion and stability of conditions necessary for injecting structures such as cantilevers. Specifically, printing a layer of a cylinder with a 60 mm diameter and a thickness of 4 mm over a height of 3 mm necessitates adding 221 ml of water before printing. The synchronous layering increase and controlled injection speed are vital for preventing layer separation and ensuring continuous workability of M1 material before it fully hardens, thus supporting the construction of overhangs and cantilevers as depicted in the setup where the nozzle injects into the water environment (Figure 6 (b)).

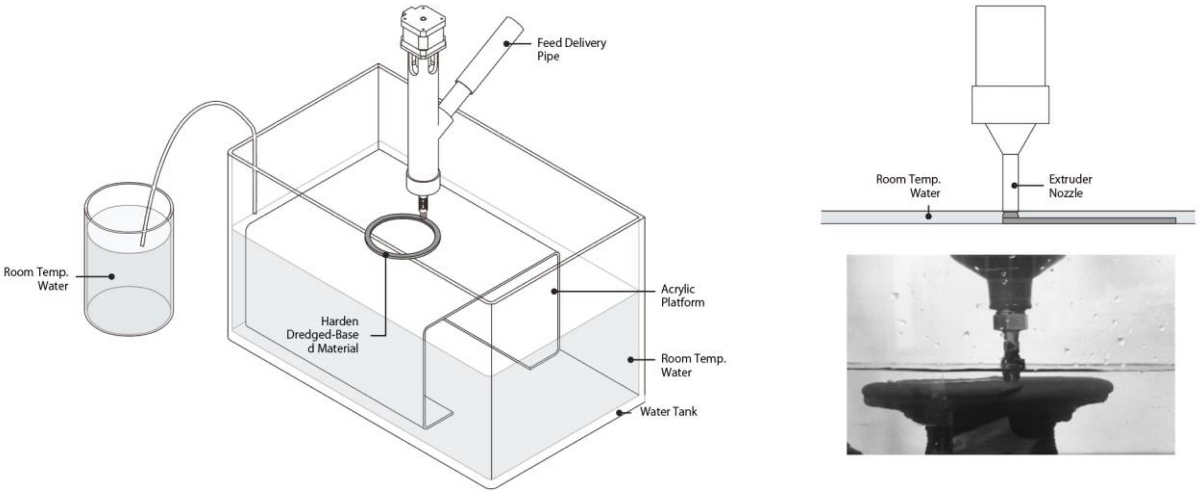

Figure 6: (a) Water tank set up (b) Injection in water environment

3. Printing Result

A key characteristic of RLP is its platform independence, facilitating seamless integration with any Computer Numerical Control (CNC) system operating on at least three axes. The minimum requirement for the RLP control platform is a gantry-style three-axis CNC machine. In this DBM printing process, the gantry machine is utilized to establish proof of concept (see Figure 7). By finely adjusting the printing speed and the flow rate of the M1 material, stable and optimized printing outcomes can be achieved. This optimization process is enhanced by the use of an air pressure regulator valve, crucial for maintaining consistent pressure levels during printing. The interplay between the valve's pressure settings and the movement speed of the three-axis gantry is critical; both parameters must be meticulously calibrated to achieve optimal conditions. This calibration ensures that the flow and stability of the M1 material are maintained throughout the printing process, facilitating the production of high-quality and structurally sound constructs.

In the initial printing trials, manual operation was adopted, introducing a distinctive aspect to the process. This approach allows for highly customized and freeform printing of concrete formworks, representing only an initial validation of the concept. The future holds greater possibilities and versatility for this technology. The following figure (Figure 8) illustrates the dual outcomes of this innovative approach: the use of the three-axis gantry machine results in smooth and uniform surfaces indicative of controlled mechanical processes, whereas manual printing showcases the ability to produce irregular and uniquely shaped structures that reflect the bespoke nature of manual craftsmanship. This holistic approach will enable the practical application of DBM injection printing technology in complex construction and manufacturing scenarios, paving the way for more innovative and efficient building solutions.

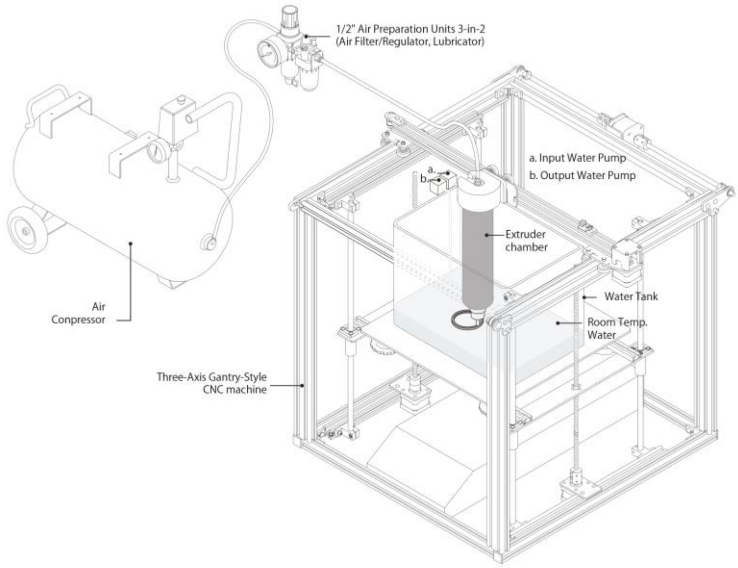

Figure 7: Injection printing set up

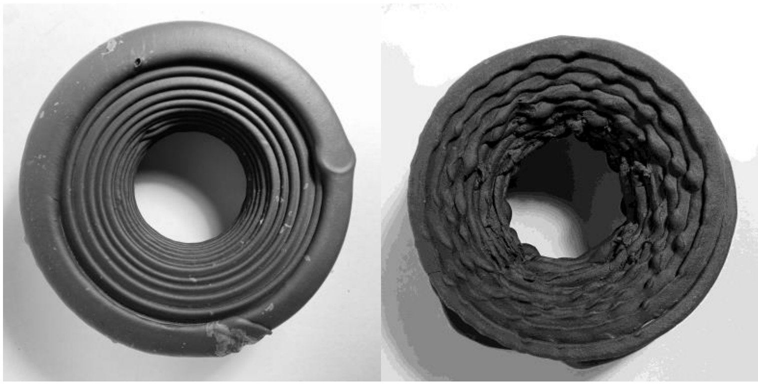

Figure 8: (a) Three-axis gantry machine result (b) Manual printing result

Traditional concrete formwork (Figure 9 (a)) refers to the temporary or permanent molds into which concrete is poured to achieve the desired structural shape during setting and curing. It plays a crucial role in construction projects, providing the necessary support to maintain the integrity of concrete structures until they gain sufficient strength to support themselves. In traditional formwork systems, materials such as timber, plywood, aluminum, and steel are commonly used. Timber and plywood are popular for their cost-effectiveness and ease of cutting to fit various shapes and sizes, making them suitable for smaller projects or unique structural forms. Aluminum and steel formworks, while more expensive, offer greater strength and durability, making them ideal for larger-scale projects and repetitive structures, as they can be reused multiple times. The design and construction of formwork require careful planning and execution to ensure safety, efficiency, and quality. The formwork must be strong enough to withstand the pressure of the fresh concrete and any additional loads from workers and equipment without distortion. It also needs to be sealed properly to prevent leakage of cement slurry and ensure a smooth finish on the concrete surfaces. After the concrete has hardened and achieved sufficient strength, the formwork is removed in a process known as stripping. This stage must be carefully timed and executed to prevent damage to the concrete. The reusable materials of the formwork are then cleaned, maintained, and stored for future use, making formwork a vital and recurring element in construction activities.

DBM concrete formwork (Figure 9 (b)) presents additional advantages over traditional formwork systems, primarily due to its innovative material characteristics. It incorporates non-petroleum-based hydrogenated glycerides (HG) as a key component. This unique material choice not only promotes environmental sustainability by avoiding petroleum-based products but also enhances the functionality of the formwork. One of the most significant benefits of using HG in DBM concrete formwork is the elimination of the need for separate release agents, which are typically required in traditional formwork to prevent the concrete from sticking to the molds. The presence of hydrogenated glycerides inherently reduces adhesion between the concrete and the formwork surface, facilitating a much easier and cleaner demolding process. Moreover, DBM concrete formwork allows for greater creativity and flexibility in architectural design. The formwork can be easily shaped into freeform and intricate structures, which are often challenging to achieve with conventional materials. This capability is particularly valuable in projects requiring unique aesthetic details or complex geometries that traditional formwork materials might not easily accommodate. The integration of DBM technology in concrete formwork, therefore, not only enhances the ease of construction and reduces the environmental impact but also expands the possibilities for architectural expression. This makes it an appealing option for modern construction projects aiming to combine sustainability, efficiency, and innovative design.

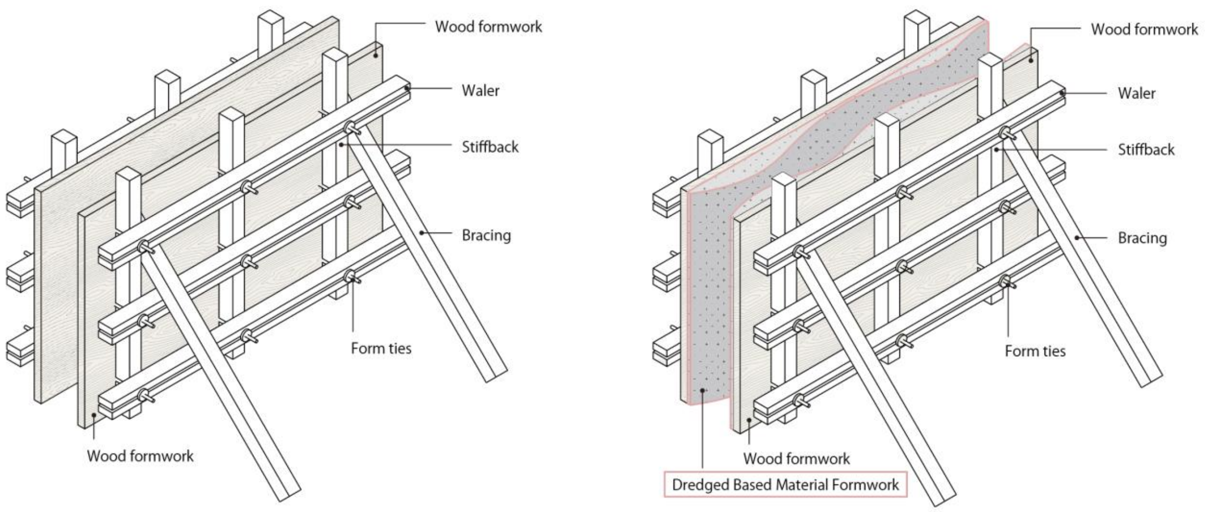

Figure 9: (a) Traditional Concrete Formwork (b) DBM Concrete Formwork

4. Conclusion: submission of contributions

This investigation has demonstrated the feasibility and potential of the DBM injection printing technology as a pioneering concept. Despite these encouraging results, there are still several challenges and unresolved issues that require further exploration to refine and optimize the technology. A critical aspect is the determination of the extrusion rate in relation to the M1 chamber and nozzle. Moreover, systematically increasing the volume of the M2 system is vital to prevent layer separation during the printing process. It is also essential to maintain consistent and systematic temperature monitoring of the M1 material to prevent premature cooling and solidification due to external environmental factors, which could lead to structural problems such as layer separation. Enhancements in printing control mechanisms, which may include integrating the extruder with robotic arms or multi-axis machining equipment, are necessary to ensure stable, consistent, and efficient material deposition. The successful application of DBM injection printing technology depends on a thorough understanding of its extrudability, processability, and constructability, which must be considered in conjunction with the overall manufacturing process and material properties. Progress in this field requires a collaborative approach that integrates insights from material design, structural engineering, and manufacturing methods to fully realize the functionality of this technology.

Recent advancements include the successful infusion of concrete into formworks made using DBM, confirming the repeatability of the material and its ease of demoulding. Additionally, customized formworks have been created using the aforementioned printing methods, and their feasibility has been validated post-demoulding, further highlighting the potential of DBM injection printing technology in innovative manufacturing applications.

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