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# A Critical Review of 3D Concrete Printing

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**ABSTRACT:** This paper is a comprehensive review of 3D concrete printing with a focus on recent publications. A full understanding of 3D concrete printing comes first from examining its history. From there, the different printers, techniques, software, and materials are reviewed. 3D printers consist of three major components: the arm, the nozzle, and the pump. Different variations of all these pieces are used to build the optimal machine to print the job. This also goes for the material printed which is most referred to as a paste, as there are different additives that can be used to optimize certain desirable characteristics. 3D concrete printing has a few limitations and challenges, but the possibilities are vast. From creating affordable and quick housing, to creating shelter for the first human on Mars, 3D concrete printing is certain to make an impact on how we think of concrete.

**KEY WORDS:** 3D Printing, Concrete, Construction, Printers, Printing Material

## I. INTRODUCTION

Modern concrete has been used for almost two centuries. One of the main components, marking the cement as modern, is Portland cement, which Joseph Aspdin is credited with [1]. Before this, the Romans used a similar version of cement. It is created by mixing lime, volcanic ash, and water. The first record of this mixture dates back to 300 BC. From that time to about 476 AD, they experimented with the recipe to increase strength and delay cracking. This experimentation is the first record of admixtures; the Romans commonly used animal fat, milk, eggs, and blood [2]. Now, concrete is the most popular building medium internationally. 4.1 billion metric tons were used in 2019 alone. One reason for concrete being the popular choice globally is that the materials are found all over the world. Also, it’s high resistance to fire and water make concrete a desirable choice for buildings and underwater structures [3].

For all these reasons, concrete has many uses. Ranging from pipes and drains, to the more commonly thought of roads, bridges, and buildings, concrete is extremely versatile. There are also many techniques for building all of these structures. Typically, pouring concrete requires a frame. This technique includes making a shape, commonly with wood, and pouring concrete in and allowing it to solidify. For most concrete mixtures, the American Concrete Institute states that this process takes at least 28 days, that is for the concrete to reach its maximum yield strength [4].

Another fast-growing technique for using concrete is 3D printing. While 3D concrete printing (3DCP) can work on a large range of scales, the design of the mixture is much less flexible. 3DCP uses a mixture with less water, and usually less aggregate, known as a paste. Then, using a pre-programmed design, an arm, pump, and nozzle system carry out said design [5]. 3DCP is known for being inexpensive, quick, and versatile. Printing concrete instead of pouring it is usually significantly less expensive because of three main reasons. The first is that form work is awfully expensive. The preparation to pour concrete takes a large amount of labor when compared to the rest of the pouring process. 3DCP excludes this cost form entirely. The second reason is that the printing process usually has little waste. From mixing to pouring there is much less concrete that ends up stuck in the mixing device or miss poured. The printers are designed to be very exact or else the structures could fail, and this also ends up cutting costs. Finally, 3DCP can also reduce transportation costs of precast structures. Walls or other large pieces of concrete that could have previously been trucked in can now be printed on site, thus saving the trucking costs and potentially large amounts of time [6]. In addition to saving time and money, the possibilities of 3DCP are infinite. While smaller printings have been used to study the strength and reliability of the printers, larger sized items have piqued more interest. All these techniques, strengths, and weaknesses will be more closely examined throughout the paper.

This paper aims to critically investigate concrete printing, its history, techniques, and usages to analyze this method’s challenges and capabilities. Various relevant and recent publications discussing the study of 3D concrete printing performed by a multitude research institutes will be compared to each other, as well as generally overviewed.

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## II. HISTORY

Stereolithography, also known as SLA or 3D printing, came about in 1980. The demand for prototypes through several fields and disciplines increased drastically. The technology and process together created to keep up with this demand became known as rapid prototyping (RP) or additive manufacturing (AM). Using his background in SLA, a researcher by the name of Hideo Kodama produced RP machinery and created two new fabrication methods. One of these methods mixes polymer to the printable plastic. The polymer reacts to UV light, causing the newly printed prototype to dry much quicker than before [7]. Kodama did attempt to file a patent, however due to a misfileCharles Hull was the first to patent the technology and create the first SLA-1 machine in 1986. Figure 1 is a sketch from Hull's official patent. It was most common to use 2D drawings: however, this practice leaves out some of the data on the object in question, so one must combine several drawings to create a complete design. The SLA-1 would typically start on one side of the design and complete before moving on [8]. All these early 3D printers printed with an acrylic material, however all who worked with these machines knew their incredible potential to do more.

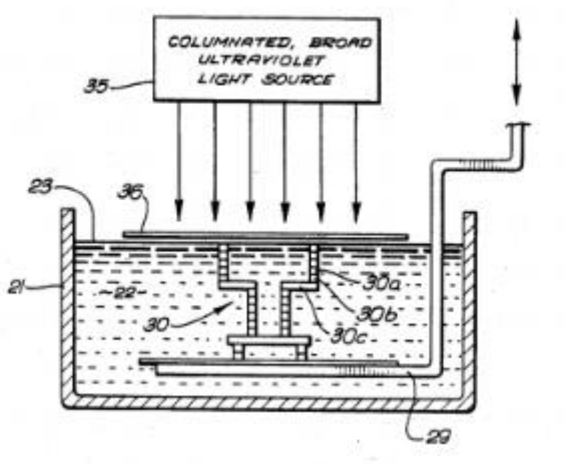


Figure 1.Charles W. Hull Official US Patent for SLA-1 Machine 1986

The sketch in Figure 1 is one of many in Hull's patent that depicts the elevation of a possible setup. The computer connection can be seen labeled at 29. This connection sits beneath the nozzle. Above this, the pieces labeled 30 a through c shows the stands that hold up a moveable light source. Parts 36, 23, and 21 help contain and align the UV light to maximize its effect [8].

The next step was to try printing with the most common building material in the world: concrete. SLA proved there was an opportunity for product reduction time. However, the change in material posed some difficulties. A common concrete mixture would be difficult to print due to its inability to keep its shape when poured. Throughout the 90's, researches focused on creating a mixture that extruded smoothly and immediately retained the desired shape [9].

By 2012, 3D concrete printing was well into the development stages, led by BehrokhKhoshnevis who developed Counter Crafting (CC), which is the deposition of layers of continuous concrete like filaments on top of each other. Khonshnevis' original idea was to use this technology as emergency shelter, however, after further development his team pointed out that the possibilities could extend to much further. Many still use this process, however it is important to note its beginnings because CC developers consider it to be the father of many other techniques [10]. Due to these findings, the accuracy of 3D printers has greatly increased, yet the prices continue to plummet. The technology is therefore more desirable to not only those working in labs but construction companies as well.

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## III. 3D CONCRETE PRINTING

3D Concrete printing is a very versatile operation due to the numerous variables. The printer and all of its pieces can be adjusted and swapped out to make the ideal printer for the task at hand. The material and the technique also have this ability. The umbrella of 3D concrete printing has the potential to accomplish so much.

### A. 3D Concrete Printers

In the simplest sense, 3D concrete printers are a robotic arm, equipped with a nozzle and pump that are programmed to release a concrete paste at a specified flow and location. Currently, there are 3 common types of 3D printers: gantry, robotic, and crane. Gantry and crane printers share many similarities. The notable difference is the crane is more capable of vertical movements. Manufacturers produce gantry and crane printers in many different sizes, while robotic printers are best at smaller sizes. Another trait the gantry and crane share is the number of axes; usually, they have 3 or 4. Robotic printers have the advantage of having 6 axes. More axes grant the opportunity for more movement and thus can fulfill more complex designs. Figure 2 is a group of images for each printer type [5].

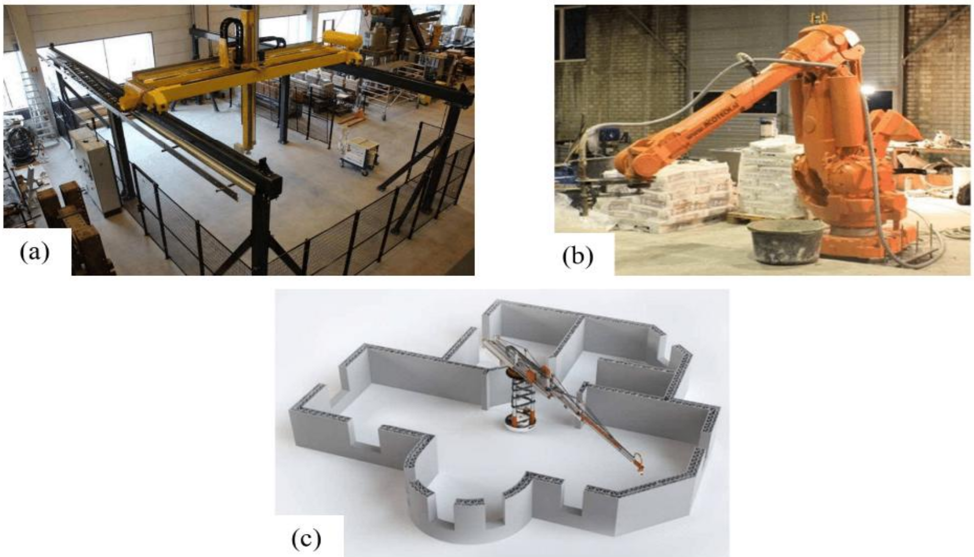


Figure 2. (a) Gantry Printer, (b) Robotic Printer, (c) Crane Printer [5]

Nozzles are a crucial piece of the printer because without the proper size and orientation, the accuracy on any of these printers would be abysmal. Circular, elliptical, and rectangular nozzles are common depending on the type of printer. The nozzle is also crucial to the finish of the concrete. Lately, trowels in the nozzle have become more and more popular. The mixing process of the paste creates the desired air content in the mixture, so as the material moves through the pipe and out the nozzle the air content must stay steady. The trowel helps to reduce unexpected air content. Some combinations of different robotic arms and nozzles yield notably better results. Although the finish depends on the nozzle, it is more common to pick the printer arm that works best on the project and given area first. Then, a nozzle that works well with the arm and still produces a semi desirable finish. Problems with finish can usually be adjusted with admixtures or post excursion tasks [11].

In 2018, Purdue University released a study where the printing set up was a combination of a gantry-based 3D printer and a motor-driven extrusion system to serve as a paste extruder. These pieces were commonly used for printing thermoplastic. When this setup is used for printing concrete, the product proved to be stronger while retaining its viscosity. This set up showed a higher yield stress as well as viscosity than other set ups. Designers used Simplify3D because it is a 3D unique modeling software that can create designs using 5 axes. The extra two axes past the common X, Y, and Z are known as E and F. The F axis represents the nozzle speed. The E axis is the amount of material extruded relative to the F axis [12].

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**B. Techniques**

Before printing, especially if on a small scale, a laminar cube structure can be printed to generate a tool path. It is important to create a solid structure covering the range that the combination printer could reach to know if anything within these dimensions causes any issues. It also checks to see if at any point in this range there is an issue with the cement paste mixture being printed just as expected [12].

For the smaller printers (with printing ranges of approximately a 25 mm cube) the material, nozzle, shape, and printing angle all work differently. When talking about this small of a structure, an opening or gap is known as a cell (Perrot 2016).

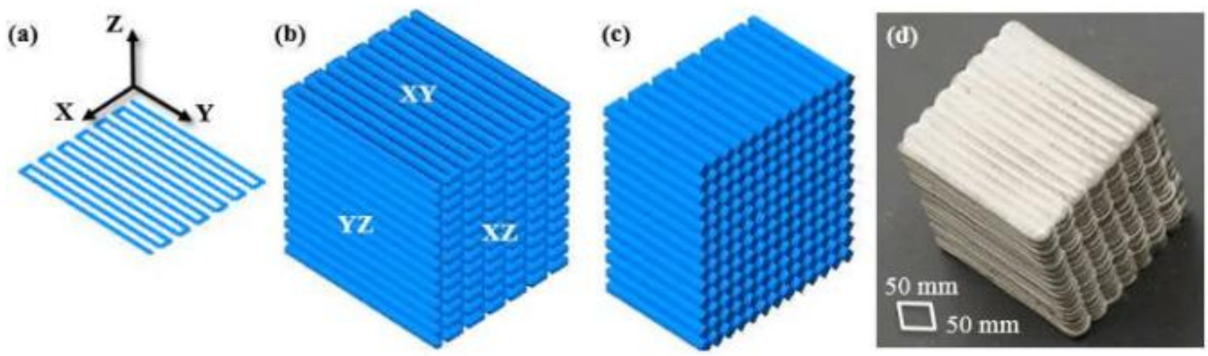


Figure 3. (a) Printing pathway for a laminar cube in the XYZ axis (b) (c) laminar structures in the modeling phase (d) image of complete 3D printed laminar cube [13].

Similar techniques as the larger printers have been tried on the smaller ones, but the structure of cell walls proves to be a challenge. Many unfruitful attempts have been made to print an object that retains a strength to size ratio when printed only a few millimeters tall. A recent successful shape has been the honeycomb. The cellulose is solid on the exterior with a webbing like shape inside, and therefore this can be compared to the more commonly understood honeycomb. When a honeycomb architecture is adapted an immediate issue is discovered. The shape doesn't display post peak load displacement behavior, so immediately it is known that although this design may prove to have a later peak point, parts of the stress/strain diagram cannot be collected experimentally, only theoretically. Values past the peak are estimated to have a full understanding of this structure. This design is then carried out at different printing angles with a 60% infill or solid. On a slightly larger scale, the cast is found to peak at the highest: around 250 N load. This, as stated earlier, is not feasible for the 2 mm scale. After that, an 8 percent slope with solid filling in the bioligand structure was found to hold a 200 N load before peaking. The strongest at only 60% infill was found to be a 45% slope. Theoretical MORs were found to be proportionally related to relative density,but it is found to be inversely proportional to the angle at which they are printed. An 8% slope is found to be the lowest percent that can be performed accurately with the materials in hand [13].

For large scale printing there are other techniques and uses. Contour Crafting is a technique where typically a large-scale printer moves around with wheels to single-handedly print an entire building. It is considered a robotic printer. Originally from a company that bears the same name, Contour Crafting Inc. meant for this system to print emergency housing quickly and cost effectively. Now, NASA and China's Space program (CNSA) are looking at using these machines to print shelter on Mars or the Moon.  This technology has caught the eye of not just China but many countries over the past decade. In the Netherlands, CyBe Additive Industries built off the CC technique and built a printer that helps the material reach its targeted strength quickly. CyBe cut the wait time to just 5 minutes. This was accomplished by a nozzle that purposely misaligned each layer. This is not typical of the original CC technique. However, the goal is to build a stable structure quickly, and this does just the trick [5].

Previously, a lot of 3D printings were created from multiple 2D models. However, now with technologies such as Building Information Modeling (BIM), the world is moving towards a 3D state of mind. In the earlier years of additive manufacturing, models were created using a coding language called Standard Tessellation Language (STL). However, this system was not created for this purpose, and it creates a lot of issues. For example, in STL it is impossible to

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represent the complex shapes, mixtures, and speeds the printers must operate with. Therefore, there are too many errors for the language to be a permanent modeling technique. Therefore, many designers have moved to BIM. There are many advantages that BIM has that STL did not. Besides the ability to form the exact necessary geometries and integrate material specifications, BIM can allow multiple designers to collaborate at once and produce complex and complete designs [13].

The collaboration possibilities of this phenomenon are endless. Teams everywhere benefit from having this 3D drawing and the ability to manipulate it easily. If construction is to move to the way of 3D, how will 3D printing be integrated? Using CAD, complex pieces can be printed layer by layer which results in a notable amount of time saved. Developers no longer must take the time to piece together a design drawing by drawing. Another factor that saves time is that the design is programmed in one fluid object. This way, the printer creates the object in the strongest, most efficient way. The list of potential benefits only continues from here. There is a great increase in design freedom, allowing designers to use shapes that although are quite strong are not easily made in forms. The need for human labor is almost none, so the possibility for unmanned space projects. Also, the cost is relatively low [6].

**C. Materials**

There are many requirements when creating a material for 3DCP, and these requirements depend on characteristics of the project. However, in general, the material must be pumpable, extrudable, and have the proper set time to stress yield ratio. Pumpability is an issue in all types of 3D printing. The material must go through a series of tubing that connects the tank that holds the material to the nozzle. To get the material through the tube, the material will undergo some pressure. This inevitable condition can cause some issues; the most notable is separation. Separation is when the elements of the concrete distinguish themselves into layers because the materials all have different specific gravities. To produce the strongest product, evenness is necessary. Although there are a multitude of additives that are used to improve certain characteristics of concrete, separation is still not easy to solve. The difficulty is a high workability is desired before printing, to easily move through the pumping system, however as soon as the material is through the nozzle the material must hold its shape. For instance, if the material is made less viscous, logically the material would have to undergo less pressure to move the same amount of material through the tubing. However, this also means there is likely more water in the mixture, and therefore the layers of separation are larger. When it is water that is separating out of a mixture it is known as bleeding. These two needs work against one another, so many studies have been centered on this issue. One theory is to reduce separation, two additives can be combined. One is for increasing viscosity and the other is to reduce water variability. These are known as high range water reducing admixture (HRWRA) and viscosity modifying admixture (VMA). Without the HRWRA, the VMA would have caused a bleeding issue. Typically, little water is used in 3DCP mixture, so it is commonly referred to as a paste. Like creating ceramic pieces on a pottery wheel, water must be added little by little. This is not common for other concrete projects; 3DCP projects only do this to keep pumpability. The ratio of water to solids can be as little as .27 percent. This is especially true for small quantities. To ensure pumpability, a specific mixture must be used [12].

Extrudability is defined as the ability of a material to move from the nozzle to the printing area as desired. It is another issue that the material choice must surpass. When printing in the most common CC style, it is important to note that the vertical stress increases with each layer [15] This means that the first layer must be able to withstand the stress from all the following layers. Vertical stress is a product of the material's specific weight, the desired height, the time passed since the first layer was printed, and the overall rate of construction. This is then compared to another calculated value known as the critical stress. The critical stress is the stress when the material fails. The time since the first layer was printed affects the critical stress, and there is a geometric factor and the yield stress that play a part in determining the critical stress as well. If the critical stress is greater than the vertical stress, then the printing rate for the specified material can be considered. Therefore, to increase the time since the first layer was printed (commonly denoted at t), the critical stress would increase more than the vertical stress because the yield stress is also affected by the time. Structural build up requires a phenomenon that cannot be seen with the naked eye known as calcium silicate hydrate (CSH) nucleation. In less than a minute after most mixtures are extruded, CSHs nucleate between cement partials. This is what mainly gives the concrete its strength. The designer will come to an issue; two ideas to produce the best quality product oppose one another. It would be beneficial to increase the time between layers to increase the critical stress but decreasing the time would allow CSHs to form between the layers rather than just within the layers themselves. Optimization equations and sectioning out pieces of a project are how most producers evade this issue [16]

When the material extrudes from the nozzle, it is particularly useful if it is in laminar flow. Laminar flow is described as when the material leaves a nozzle in a constant smooth shape. Without laminar flow, it is much more difficult to create a precise object. Also, a bent nozzle allows for non-orthogonal printing, meaning that structures can be optimized to a better shape than their orthogonal printing or form casting counter parts [17].

### D. Testing Procedure

2D radiographs are taken of these laminar cubes from various angles, this gathers information on the microstructure. Then, using X-ray microscopes employed for micro-CT characterization technique, flat panel detectors significantly enlarge the images and therefore minimize clarity, however the positive to this technique is the entire volume can be scanned at once. After preparing the x-rays, it is found that the pore network (at both macro and micro scale) appeared to be aligned with respect to the direction of the filaments in the lamellar architecture of the printed specimen. Micro-CT demonstrated great aptitude (as non-destructive technique) for capturing spatial heterogeneities of the microstructure of 3D-printed elements as large as 10s of mm. The dual-stage magnifications system used in this study facilitated higher resolutions at large working distance, thus allowing CT of larger specimens. Then, laminates of each of the specimens are examined using a magnetic microscope. The positive of needing to print, is the cracks, is that before we reach the peak on the stress strain diagram, we can see a crack through just one laminate. This, ideally, could follow the idea of reinforced concrete, where the concrete would crack before the steel would yield. Imagining practical use for this machinery is now immensely expanded because of the “telltale, yet not critical” signs of failure.

## IV. UNMANNED SPACE MISSIONS

The need for human labor is almost none, so there is a use for 3D concrete printing in unmanned space projects. As previously discussed, NASA and CNSA (China National Space Association) are looking into producing large enough mobile gantry printers to use contour crafting to build shelter for future manned missions. The weather on Mars can be intense, so as these programs look to find safe ways to launch their manned missions to the red planet, shelter is one of the first thoughts. The printers are relatively low cost, and unmanned recon missions must be run anyways. The sensors for these robots are the most impressive piece by far. NASA itself admits that these missions can deviate from the course a small amount. For example, rockets would be launched seven months before they landed on Mars. It is impossible to perfectly predict weather and other underlying conditions, so the transport may not land exactly where calculated. So, these sensors must first scan the surrounding area to decide if it is a suitable spot to build. From there, either location must be adjusted, or the design does. Hopefully, this equipment would be capable for either task. One of the advantages of using 3DCP to build shelter on extraterrestrial missions is the possibility of using Martian or lunar soil. Not only would there be little to no labor requirements, but one of the main components of concrete wouldn’t have to be shipped to the site. NASA has mostly been researching 3DCP for possible use on Mars. The soil on Mars is rich in sulfur, and the potential material that would make the shelter is known as sulfur concrete [17]. A study was done to optimize the sulfur to soil ratio, as well as test the possibility of more additives such as metals or glass. The study yielded a result of a sulfur concrete maximum compressive strength of 4.9 ksi, but with added glass fibers this result was increased to 6.6 ksi [18]

## V. CHALLENGES

There are also a few challenges. Firstly, the material that we are printing cannot be normal concrete. While printing, the first layer must have yield stress that is high enough to hold the next layer. This becomes more difficult with each layer. This is difficult to accomplish while not allowing the shape to change, for the goal is to work without forms. A recent suggestion has led experts to wonder if the thixotropic property of the cementitious material would be helpful because of its high yield stress to low viscosity ratio.

A second concern is transportation. Depending on size, it is possible to print in pieces, transport, and finalize construction.

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Another concern is concrete finish. The printing process creates challenges if not properly prepped and cleaned. Along with unexpected deposits, improper control of the material may lead to voids and other similar issues. The most suggested solution is to add trowels in the nozzle.
The process is too expensive as well as time consuming, and the environmental impact is enormous. The two most popular solutions are additive manufacturing and 3D printing.
Within reasonable aggregate size, the pumping system has been one of the least common problem pieces. However scarce, the most common issue is separation of the concrete mixture under high suction circumstances. As for printing material, the average concrete cannot be used. Ideally, zero slump concrete would be used because conventional casting methods are not feasible due to the interior structure.
The challenge with reinforcement is when to add the rebar. How can rebar be added if the printing is adding layer after layer? And if the goal is to set quickly, adding at the end has proved difficult [6].

## VI. CONCLUSION

Concrete is the most used building material in the world. It started as a mixture of lime and ash used by the Romans, but it has since proved to be extremely versatile. 3D concrete printers can come in many forms;however, all follow the general set up of a robotic arm, nozzle, pump, and computer. The printing techniques also vary, the most common being the laminar style, starting from the surface and adding layer on layer. For most 3D printers, a paste must be used. This consists of just cement and water. For larger printers, some fine aggregate is used. There are some additives that greatly increase the yield strength in smaller printers. The printed objects are then put under compressive strength tests and examined under a radio microscope. All these new studies and developments are leading to the attempt to use these machines in unmanned space missions to build shelters before humans arrive. Although these machines have a lot of potential, some common problems include the inevitability of a slight slump of concrete after printing, the difficulty of adding reinforcing steel, and many more. There is still plenty that can be done to research and improve 3D concrete printing.

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