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3D CONCRETE PRINTING: MACHINE AND MIX DESIGN

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ABSTRACT

3D concrete printing is an innovative construction method that promises to be highly advantageous in the construction field in terms of optimizing construction time, cost, design flexibility, error reduction, and environmental aspects. Concrete is extruded through a nozzle to build structural components layer-by-layer without the use of formwork or any subsequent vibration. The contribution of this study is to identify and resolve the various design and operational constraints of 3D concrete printing, which are of vital importance for future development of this construction technique. This paper broaches the topic in two different phases: designing the printing machine on one hand, and designing the concrete mix to be used on the other. Experimental results are presented concerning the mix design and the tests performed to determine the fresh and hardened concrete properties. Due to the scarcity of published studies on concrete properties used in 3D printing, the results might be invaluable to the future of this technology. The study may lend itself to become the blueprint for future bigger-scale projects such as creating whole buildings using 3D concrete printers.

Keywords: Buildabilty, Concrete, Contour Crafting, Flowability, Open Time, 3D Printing

1 INTRODUCTION

3D Concrete printing is a construction method that has the capability of fabricating a predesigned building element in 2D layers on top of each other, the repetition of which completes a 3D model. The concrete, which is poured out of a printing nozzle, doesn't need any formwork or subsequent vibration. Contour Crafting (CC) is one method of concrete printing that shows great potential in improving construction techniques and methodologies. CC constructs objects layer by layer using robotics; it is used for small-scale industrial parts and also was identified as the only method capable of delivering components large enough for building structures [1].

Several companies have been experimenting with different methods and technologies of 3D printing. The Chinese company, WinSun, has recently demonstrated its knowledge in 3D printing after printing 10 houses in under 24 hours, with each house costing a mere $5000 [2].Universe

Architecture have created the largest 3D printer in the world that uses sand and a chemical binding agent to create a stone-like material. 3D Concrete printing aims at enhancing construction on several levels: it minimizes the duration of the construction process by eliminating some time-consuming processes in the traditional method [3], it reduces costs incurred on the project by minimizing waste and overproduction in addition to minimizing the use of labor [4], it provides flexibility in building structural shapes that aren't possible to build conventionally, and delivers an improvement in the overall safety and environmental impact of the structure [5].

This paper focuses on the materials aspect through developing the concrete mix for use in this technology. Several tests were conducted to find the optimal concrete mix for this function. It also studies the printing mechanism of the 3D machine and proposes a suitable design for the printer. A structural specimen is printed as a proof of concept for the printing technique.The outcomes of this research and its applications to real-life construction practices target the need for improved automation in civil engineering projects, the need for efficiency in resource management and a rapid and less expensive construction method.

2 METHODOLOGY

2.1 Materials: Mix Design

The concrete mix must be designed to meet certain vital criteria that have a direct relationship with the methodology of printing the concrete. Thus, it is critical to ensure a complementary connection between the designs of the mix and printing machine. In order to design the optimal mix, certain target goals were set for the mix. Table 1presents these goals.

Table 1: Mix Goals

Maximize compressive strength		Maximize workability
Maximize flowability in the system	YET	Maximize buildability upon pouring
Maximize speed of concrete setting		Maintain appropriate setting rate so as to ensure bonding with the subsequent layer

As is noticeable from the table above, some of the goals seem to conflict with each other and thus the challenge is maintaining an appropriate balance of all. For instance, maximizing the compressive strength in the mix means minimizing the water-cement ratio. However, a certain water content must be maintained to ensure appropriate workability of the concrete. In addition, the mix in the system must be flowable but upon pouring must be buildable and able to hold itself and subsequent layers. Finally, when poured, the mix should set as fast as possible but not fast enough to ensure appropriate bonding with the subsequent layer.

In order to address these goals, specific measurable criteria of the mix were set .The five most important aspects of the mix that are studied are extrudability, flowability, buildability, compressive strength, and open time. Extrudability and flowability are related to the concrete extrusion, flow, and workability, as the aim is to reach a continuous easy-flowing paste from the source to the printing nozzle. Buildability refers to the ability of the concrete layer to hold the layers above it without collapsing. The concrete must also be of a certain suitable compressive strength. Finally, open time studies the change of concrete flowability with time. The goal is to ensure that each printed layer has the capacity to hold itself and harden when poured, and yet stay liquid enough to bond with the layer above it and not become a separate entity. On the other hand, the concrete paste must have a certain flowability upon its transfer that must not threaten its ability to stiffen upon pouring.

Aggregates of a maximum size of 2mm were selected as the diameter of the printing nozzle is relatively small (2 cm). Other dry constituents include cement type I and sand. A superplasticizer (Viscocrete) is used with the mix to ultimately increase the workability of the concrete and compensate for the low water-cement ratio. An accelerator is added to the concrete mix allowing it to settle and gain strength at a faster pace when poured. In addition, a retarder is also added to prevent the concrete from settling early in the tank. An appropriate balance of all the constituents has to be reached to ensure proper functioning of the mix. Several experiments were performed in order to determine the exact quantities of materials to be added for the optimal mix. An optimal amount of the different additives had to be found. In fact, quantities of superplasticizers exceeding the found optimum amount might give unwanted results [6].

2.2 Mechanics: Machine Design

The design of the appropriate machine that would function as a 3D printer for the concrete mix is critical to the project success. Several criteria had to be taken into consideration during the design, as the machine had to account for both the fresh and the printed properties of the concrete previously discussed. The machine is basically composed of three main components: the concrete tank and pumping mechanism, the printing nozzle, and the motion control system. The concrete starts its journey at the tank and is manually pumped to reach the nozzle, which is responsible for pouring it. The machine is designed to move on a tri-axial plane (x-y-z) in order to print a 3-dimensional element.

2.2.1 Motion along the Axes

The machine was specifically designed to print a specimen composed of a 77 cm x 10 cm structural wall, with the intention of printing larger elements with further progress with the experimentation. The wall was printed in two parallel lines, each 77 cm in length, and 2 cm in width, with a distance of 10 cm between the lines. Thus, the nozzle should be able to print one line on the longitudinal axis (x-axis), and then move along the perpendicular axis (y-axis) to get in position to print the other line, parallel to the initial one. Finally, it must be able to move along the z-axis to print layer-upon-layer and complete the 3D design. The height of each layer is designed to be 2 cm and so the machine is designed to move up in 2 cm intervals.

The main part of the machine is a vertical element that supports the mobile tank and nozzle. This element is responsible for motion along the z-axis and can be operated both hydraulically and manually. The element was designed to roll on a specified track along the x-axis, and its motion is along a threaded horizontal bar. The motion on the x-axis is controlled by a rotating drill of adjustable speed. Finally, the nozzle held by this element is able to move in a direction perpendicular to that of the machine motion and change positions on the y-axis.

2.2.2 Nozzle Design

Another critical element that has a high impact on the extruded concrete properties is the nozzle. The nozzle diameter has a direct relationship with the concrete mix properties, specifically its flowability. As the diameter size decreases, the flowability of the mix should be increased to account for it and vice versa. In addition, the nozzle has two trowels, a side and top trowel, which lag behind it. The side trowel on the outer side functions to straighten the concrete being poured as the nozzle passes by. The top trowel serves to straighten the upper surface of the concrete layer to ensure maximum buildability.

Before designing the nozzle, the group experimented with syringes of different opening diameters ranging from 1 cm to 2 cm. This was done to determine the optimal diameter the nozzle was to have. The diameter size that proved to be most optimal for the nozzle function 2 cm. A diameter greater than 2 cm caused buildability problems as the layer wasn't able to hold itself while a smaller diameter presented segregation problems of the concrete components.

2.2.3 Tank and Pump Design

The function of the pump is basically to transport the concrete paste from the tank to reach the nozzle, where it is subsequently poured. The pump to be used has to be able to handle the specified concrete mix, and account for several aspects such as the maximum aggregate size and the water cement ratio. Since no pump (to this specific small scale) exists that is able to account for the concrete pouring mechanism required, a "piston-pump" was designed instead to carry out this purpose. This pumping mechanism combines the syringe pressure methodology on one hand, and the concept of the cement screw pump on the other. The cement screw pump, or shotcrete pump, couldn't be used since it exhibited very high pressures and wasn't suitable for our project scale. Even at low pressures, the machine sprayed the concrete with air and thus wasn't appropriate for this application.

The pumping instrument finally designed is directly integrated with the tank as it functions by pushing the concrete down by a force exerted on the piston. The tank used is a cylindrical mobile tank that is connected to the machine and moves with it. At the bottom of the tank is the printing nozzle. The most critical element considered is the pressure exerted by the pump on the mix. This pressure directly affects the speed at which the concrete is being poured. The goal is to find an ideal association between the two.

2.3 Testing Procedures

The choice of the optimal mix necessitates several tests to be conducted, keeping in mind the target parameters to be achieved mentioned in Section2. These factors together contribute in equal importance to the printing process. Firstly, preliminary trial tests are done that target extrudability, a critical parameter that ensures the proper printing out of the nozzle. This is primarily affected by the quantities and distributions of the dry constituents in the mix. To determine the starting mix proportions, the concept of slip-form concrete design, which has a self-compacting property and does not require further consolidation, was followed [7]. Once the obtained paste is found extrudable, several tests were performed to meet the other requirements. The quantities of additives then start to play the prominent role. Below is a description of the tests performed to ensure following target criteria are met:

- Extrudability: It refers to the capacity of the concrete to be extruded out of the nozzle. This is assessed on the basis of the distance over which the paste can be printed without blocking the nozzle. Also, the printed paste should be clear of cracks and separations.
- Compressive strength: The target strength of the concrete is determined using BS 1881-116:1983 and 5x5 concrete cubes [8]. Strength is particularly important since what is printed is the structure in layers rather than its entirety at once. Since setting time should be assumed to be instantaneous, and since the printing process happens only in a matter of minutes, the target strength and strength gain should be high.
- Flowability: Measurement of flowability is achieved by performing the slump flow test [9]. The concrete is spread out of an inverted cone. The time required for the mix to spread by a specific diameter is measured and the rate of flowing can subsequently be obtained. An easily expanding mix corresponds to a greater flowability and workability.

- Buildability: this is measured by the number of layers of the printing specimen that can be achieved without collapse. The target average number of layers is 5.
- Open Time: This criterion is important since the printed concrete isn't poured in one go as in the traditional method. In the latter, the initial and final setting times are more representative but do not have much relevance in concrete printing[10]. Thus, open time measurement is a better representation of the concrete workability change with time. It is calculated using the slump flow test to get the flowability over specific time intervals.

3 RESULTS AND DISCUSSION

3.1 Machine

It is essential to find a balanced relationship between the extrusion rate of the mix and the machine speed. After calculating the extrusion rate of the optimal mix, the machine speed was adjusted as to maintain the appropriate criteria for printing. The extrusion rate of the concrete paste from the nozzle was calculated to be 0.09 Liters/sec. Thus, the appropriate velocity that was compatible was set as 18.76 cm/sec. The final printing machine, designed according to the criteria described previously, is shown in Fig. 1 below.

Fig.1. The 3D printer built machine

3.2 Experimental Results for the Concrete Mix

An extensive series of experiments had to be conducted to reach the final optimal mix that can be used for concrete printing. The optimal mix is defined as the mix with the lowest water-cement ratio that is able to meet all the required set standards. As for any correct experimentation process, a control mix had to be obtained. To reach the control mix, several mixes with varied proportions of dry constituents (sand, fine aggregates and cement) and water-cement ratios were tested regarding their extrudability from a set of syringes with varying diameters. The diameters ranged from 1 cm to 2 cm and mimicked the role of the nozzle. Note that the extrudability criteria were tested visually by the capacity of the mix to exit the nozzle of the syringe in a continuous flow. In addition, after pouring, the concrete paste must set with minimal cracks. It was observed that increasing the amount of cement and decreasing that of sand gave better extrudability. After several trials it was found that the most suitable mix was composed of a fine aggregate to cement ratio of 1.28 and a fine aggregate to sand ratio of 2. The dry constituents are no longer to be varied for the rest of the experiments. The minimum water/cement ratio that made the mix extrudable was 0.48. In addition, the optimal nozzle diameter was set as 2 cm due to blockages and segregations caused by smaller nozzle sizes.

After finding the optimal mix, other experiments required trials with additives. A superplasticizer was added with the role of decreasing the water-cement ratio to increase strength while maintaining an appropriate flowability. As the water cement ratio is decreased and plasticizer is added, the mix becomes more flowable. However, after a certain point when the plasticizer added reaches a specific amount, the mix will no longer be appropriately buildable. In other words, the mix will become too fluid and unable to support itself. Thus, it is necessary to find the right balance between flowability and buildability. Five mixes were tested as shown in Table 2 starting with the control mix and decreasing the water-cement ratio (while adding plasticizers) until the mix is no longer buildable.

Table 2: Testing of Superplasticizer

Mix Number	Cement (gr)	Sand (gr)	Fine Aggregates (gr)	W/CRatio	Superplasticizer (mL)	Flowability rate(cm/sec)	Retarder (mL)	Accelerator (mL)
1 (Control)	125	80	160	0.48	0	-	1	0.5
2	125	80	160	0.42	0.5	1.1	1	0.5
3	125	80	160	0.39	1	1.13	1	0.5
4	125	80	160	0.38	1.1	1.2	1	0.5
5	125	80	160	0.36	1.3	1.4	1	0.5

In addition, both a retarder and an accelerator were added before pouring the mix. The retarder has a long term effect to delay the setting time of the concrete which is necessary to ensure the concrete doesn't set while being transported and before pouring. On the other hand, the accelerator is added directly before extrusion and functions on the short-term to ensure the appropriate setting of the concrete when poured. The amounts of retarder and accelerator were chosen to ensure sufficient testing of the mixes. They will be later optimized through other tests.

After conducting the compressive strength test, the strengths for samples 1, 2, 3, 4 and 5 were 40.6 MPa, 41.5 MPa, 42.3 MPa, 43.5 MPa and 55.4 MPa respectively. Thus, it is apparent (and expected) that the smallest water-cement ratio resulted in the highest strength. The mixes all met and exceeded the target compression strength set at 40 MPa. Flowability and buildability are therefore taken as the main requirements to test efficient printing.

The slump-flow test was performed on the five mixes to measure flowability. Flowability is important to ensure the facilitated transportation of the concrete paste from the tank to the nozzle. Flowability is measured by the diameter of the spread concrete over time. Referring to Fig. 2, Mix 1 (control mix) exhibited a low unacceptable flowability and was disregarded. The flowability graph in Fig. 2 (in blue) shows the flowability rate increasing from mix 2 to 5 with the increase in plasticizer percentage.

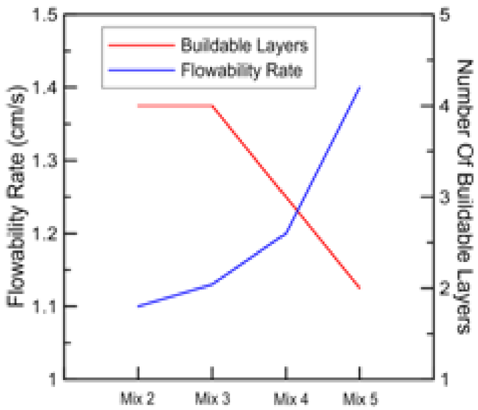

Fig. 2 Assessment of flowability and buildability of different mixes

The buildability test, conducted to assess the ability of lower layers to sustain the imposed load of the other layers on top, is shown in the red graph in Fig. 2.The maximum number of layers that could be built without collapse is measured for each of the 4 mixes. From Fig. 2, it is observed that the number of layers decreases as the superplasticizer used increases. Buildability is high for mixes 2 and 3 but exhibits a steep decrease upon reaching mixes 4 and 5.

It was observed from the results that in order for the concrete paste to meet the desired standards of workability and buildability, the flowability rate should be strictly between 1.0 and 1.2 cm/s. Below 1 cm/sec, the mix provided extrudability problems and wasn't flowable enough while a flowability ratio above 1.2 cm/sec proved unsuitable regarding buildability. The flowability ratios of mixes 2 to 3 fell within the acceptable flowability range and the poured layers were able to support themselves when extruded. On the other hand, mixes 4 and 5 exhibited flowabilities on the high range which negatively impacted the ability of the concrete to settle appropriately when poured. As is apparent from the two graphs, the optimal mix that best met the flowability and buildability criteria is mix 3. As a result, it was chosen as the optimal mix to carry the tests on.

Furthermore, Figs. 3 and 4 show the effect of retarder dosage (varied from 0 to 1.5%) on workability with time. From both graphs, it is apparent that the optimal retarder concentration is 0.5%and achieved an open time of 70 minutes. As the retarder concentration is further increased, the open time decreases very steeply to 20 minutes at 1%.

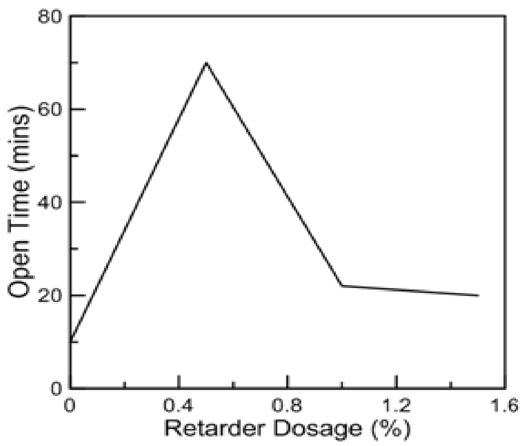

Fig.3 Effect of retarder dosage on open time

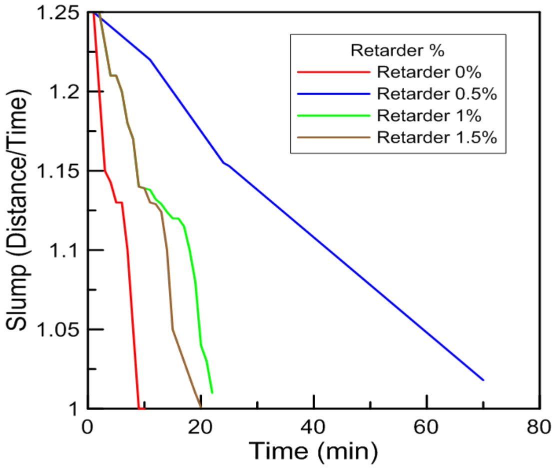

Fig. 4 Effect of retarder dosage on workability with time

In addition to that, the following tests involved adding an accelerator to facilitate the settling and setting of the concrete paste once poured out of the nozzle. Table 3 presents the three trials done on mix 3. It was observed that adding an accelerator above a certain amount (1 ml) caused an adverse effect on the extrudability as the paste was no longer able to be extruded from the nozzle (Mix 3c). Also, using too little an amount of accelerator (Mix 3a) required a long time to take effect and was not opted for. The most suitable mix in which the accelerator acted at the right time without affecting other criteria was Mix 3b (1 ml of accelerator). Finally, the optimal mix was tested on the machine and a wall specimen 77 cm in length, 10 cm in width, and 10 cm in height was printed (Fig. 5).

Table 3 Testing of Accelerator

Sample	Cement	Sand	Aggregate	Accelerator	SP	W/C
3a	125	80	160	0.5 ml	1 ml	0.39
3b	125	80	160	1 ml	1 ml	0.39
3c	125	80	160	1.5 ml	1 ml	0.39

Fig. 5 Machine printing (left) and printed specimen (right)

4 CONCLUSIONS AND RECOMMENDATIONS

3D Concrete Printing presents itself as a promising tool in the construction industry. With a mix that satisfiesvarious design and operational constraints, houses can be built using this innovative technique without the use of formwork. The printer moves in three directions to construct a wall, and eventually other kinds of structures. The nozzle that pours concrete is designed in a way to optimize the extrusion process, namely with a diameter of 2 cm and with two attached trowels lagging behind it. The appropriate mix proves itself to be extrudable, flowable, buildable and of an appropriate strength. Experimentation on various mixes revealed that the optimum mix to achieve such an outcome consists of 125g of cement, 80g of sands and 160g of fine aggregates with a w/c ratio of 0.39.Also, 1 mL of accelerator and 0.625 mL of retarder are added to that quantity of the mix in order to optimize the performance. The compressive strength of such a mix is approximately 42 MPa.

The application of the printing prototype in this paper to real-life construction is very effective, at least for small-scale structures. Such a technique can easily be used in developing countries, which are in need of a suitable, low-cost and fast building construction method. It can also equally well be used for large buildings, should the logistics for this purpose be available. 3D concrete printing offers savings in terms of long-term cost, time, labor and complexity, which are very important current factors in the construction industry. Furthermore, it is less harmful to the environment than more traditional construction methods. In addition to being a promising tool to engineers in terms of structural design, 3D concrete printing is also a potential tool for architects in architectural design. As the method is not limited by any type of formwork or manual labor, designers will have much more design flexibility in that scope.

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