Comprehensive Investigation on the Use of 3D Concrete Printing in Structural Applications

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Abstract

The study was conducted to develop 3D printable high performance concrete mixes for the Cornell University Bovay Laboratory Complex and Professor Nair Research Group. For that purpose, requirements of mixes were identified, and characteristics of mixes were tested using conventional techniques - such as compressive strength test using hydraulic press, 3D printing of a sample column, and large-scale testing of the print. The study can serve as an example for developing concrete mixes for other facilities and equipment, since it covers important properties of concrete mixes and the measures of qualitative or quantitative testing of them.

1.Introduction

The conventional method used for constructing concrete structures is formwork, which is employs creation of a form using wood and metal; concrete is poured into the form, and the form is removed when concrete finally hardens. Recently, an alternative method for creating concrete structures was developed - 3D printing of concrete. 3D printing process utilizes extrusion of pre-mixed mortar onto a pallet or any other space dedicated for the print with a layer-by-layer additive manufacturing method. That is, material is placed in layers that lie on each other. Worth noting, in this study terms “mortar” and “concrete” will be used interchangeably albeit there is a technical difference between them.

3D printing process can optimize material use, time and human labor involved in the process of creating concrete structure and allow creation of more complex and efficient structures. Developing a 3D printable concrete mix that can classify for Ultra-High Performance Concrete (UHPC) would be beneficial since it can be coupled with the benefits of 3D printing. Some studies indicate that UHPC can allow us to implement innovative solution to existing challenges [1] and 3D printing might be one of these new approaches. It has already been developed and used in studies[3], but, from our experience, employing the exact same concrete mix as outlined in other studies does not produce the concrete of same quality due to different characteristics of materials, such as particle sizes of aggregate sand and primary materials and their class and type.

Therefore, this study aims to develop a concrete mix with similar characteristics specifically for Cornell University Bovay Laboratory Complex and Professor Nair Research Group. Due to limitations discussed above, separate concrete mixes were created and tested with considerations of availability and obtainability of materials, their sustainability features, and restrictions imposed by current lab equipment.

The process of mix development involved creating combinations of materials dedicated for concrete mixes, evaluating workability features during mixing process, preparing and testing samples to quantitively evaluate compressive and flexural strength of concrete, satisfying the flowability requirements of concrete for printers, and conducting printing and large-scale testing of concrete structure. Large-scale testing would allow to evaluate the suitability of 3D concrete printing for structural applications.

The printer for this study is a Robotic Arm XTreeE 3D printer, which consists of ABB Robot Model IRB 6650S with 3.9 m arm reach and a

3.7 m IRBT 6004 Track, as in Figure 1. Additionally, concrete mixes were created for a custom 3D Gantry Printer, which at the current time is in development. The compressive strength requirement for gantry printer concrete mix is 20.7 MPa, which is a specification of structurally applied concrete [2]. Due to current non-availability of the gantry printer, the printing and large-scale testing sections of this study are fully devoted to the XTreeE printer, and the structure chosen for the first print is a hollow square column.

Figure 1: Printing Setup

2.Materials and Methods

2.1. Mix requirements and development materials and technique

The requirements that should be satisfied are established by ASCE standards, and the limitations of printing procedures.

The materials used in development of concrete mixes are Class F Fly Ash, sieved Sand, Silica Fume, Water, High Range Water Reducer (HRWR) for increasing flowability of concrete mix, and Portland Cement. The Gantry printer mix materials additionally include a polymer liquid styrene butadiene rubber (SBR), which acts as a glue and increases the bond strength between layers of concrete.

The mixes can further be enhanced via addition of an accelerator admixture, which speeds up the hydration process and allows to achieve higher strength of concrete at earlier age. Alternatively, fibers made of basalt, steel, or other materials can be added to a mix.

The mixing was done using a mixer with 5L volume capacity and low and high speeds. During mixing process, dry materials were first added together and mixed until uniform mix was achieved. With mixing done at low speed, premixed liquid components were added over the course of 30 seconds to the bowl, 30 more seconds were then allowed for achieving a uniform paste. In the case of fibers used, the fibers were added after liquids over the course of 30 seconds and then 30 more seconds were spent to achieve uniformity of the mix. After that, the mixer was stopped, the mix was scraped off the walls of the bowl to ensure that there are no dry materials left, speed of mixing was changed to high, and the paste was mixed for another 5 minutes. This results in total mixing time of 6 and 7 minutes without and with addition of fibers respectively.

In total, more than 20 mixes and variations were designed, and some of the mixes are presented in Table 1. The new HRWR that the lab is going to use is marked with asterisk and has a name Silka Viscocrete 6100. The numerical values are the masses of ingredients in grams per 1kg of a mix. For printing purpose, mix M2 was chosen, while mixes M1 and M3 were discarded due to some of their properties. As for the gantry printer mixes, M_SBR3 was chosen as the most suitable mix.

For mixes M1, M2, M3, M_SBR1 sieved sand of size up to 0.85 mm was used, while for M_SBR2 and M_SBR3 sand was sieved to maximum particle diameter of 2mm.

Mix #	Cement	Fly Ash	Silica Fume	Sand	Water	HRWR	SBR
M1	319.27	91.20	45.60	418.14	113.27	12.52	0
M2	296.62	84.74	42.37	451.23	121.57	3.47 *	0
M3	316.84	15.99	113.44	421.29	104.95	27.49	0
M_SBR1	286.36	81.82	40.91	435.59	82.28	3.30 *	69.74
M_SBR2	321.01	91.72	45.86	360.51	75.91	0	104.99
M_SBR3	356.81	0	106.29	391.68	69.39	10.82	65.01

Table 1: Mix Specifications

2.2. The specific targets posed by 3D printing – XTreeE printer

2.2.1. Flowability

The flowability of mixes was measured using a flow test as shown in Figure 2. The cone is filled with newly mixed concrete and raised. The diameter of a spread concrete is the flow value used to numerically evaluate the flowability of a mix.

Figure 2: Flowability Test

For a constant extrusion volume of 2.2 liters per minute, there is a relationship between a layer height and a spread diameter that can be determined. The graph in Figure 3 shows this relationship between print layer height and a flow of a concrete mix for the XTreeE printer. In our printing procedures, layer height of 7 mm is used, which corresponds to a 17cm flow. That was the target value for our mixes during development stage, and that is the exact value measured for mix M2.

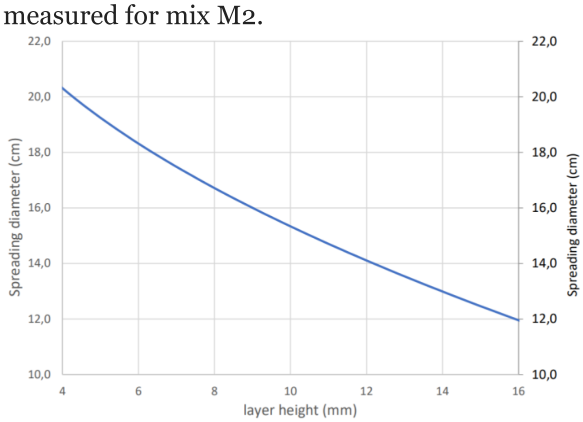

Figure 3: Relationship between Spreading Diameter and Layer Height of Print

2.2.2. Pumpability

The pump used for XTreeE printer can operate with a maximum particle size of 2mm, which imposed restrictions on the allowable sand particle diameter and the use of basalt fibers. Therefore, none of the XTreeE printer mixes incorporate fibers. Additionally, the use of fibers is not possible since it would lead to clogging of the hoses or components of the extruder head. The pumpability was evaluated through qualitative visual analysis and the satisfaction of requirements mentioned before.

2.2.3. Compressive and Flexural Strengths

The compressive strength of mixes was measured using a hydraulic press with capacity of 60000 psi. The samples were prepared using plastic cylindrical molds and had height of 4 inches and diameter of 2 inches. The concrete was poured in the molds first to a half of the volume, it was then tapped 25 times with a small metal rod to make sure that it fully fills the mold and that there are no big air voids inside. It was then poured to the top of a cylindrical mold and tapped 25 times again. The mold with concrete was then placed on a shaking table and shaken for 5-10 seconds to remove any final bits of air.

After that, the lid was secured, and the cylinders were put in a curing chamber for 24 hours for concrete to harden. The cylinders were demolded and placed in a curing chamber with temperature of 28℃ into a water bath to sit for 6 days. Due to time limitations, the first concrete sample were only cured in total for 4 days to determine the promising concrete mixes, but after that total curing time was increased to 7 days. All of the mixes presented in this study had a curing time of 7 days.

After curing, the cylinders were dried and put into special cups and loaded using a hydraulic press at a rate of 0.05 inches per minute as in Figure 4. The compressive strength was calculated using the force at which the cylinders cracked or shattered and the following equation:

$$P = \frac{F}{\pi r^2}$$

, where P – compressive strength (psi), F – force (lbs), r – radius of a cylinder (in)

Figure 4 : Compressive Strength Test Setup

3 samples were prepared for testing compressive strength of each concrete mix.

The flexural strength of mixes was measured using the same hydraulic press with capacity of 60000 psi. The samples were prepared using rectangular metal molds and had dimensions of 12 x 2 x 2 inches. Concrete was poured to the top of a mold, and the mold with concrete was then placed on a shaking table and shaken for 5-10 seconds to remove bits of air.

After that, the molds were placed in a curing chamber for 24 hours for concrete to harden. The molds were removed, and concrete beams were placed in a curing chamber with temperature of 28℃ into a water bath to sit for 6 days. That way, total curing time was 7 days.

After curing, the beams were dried and prepared for flexural strength test. Height and width of each beam were first recorded, and 1 inch was measured on each side of the longer side of a beam. The chunk between them was divided on 3 equal parts and marks were placed. Then, according to the marks, the following setup was constructed as in Figure 5.

Figure 5: Flexural Strength Test Setup

The beams were loaded at a rate of 0.05 inches per minute. The flexural strength was calculated using the force at which the beams cracked and the following equation:

$$P = \frac{Fl}{wh^2}$$

, where P – flexural strength (psi), F – force (lbs), l – length between two marks on the edges (in), w – width of the sample (in), h – height of the sample (in)

3 samples were prepared for testing flexural strength of each concrete mix that satisfied the compressive strength requirements.

2.3. The specific targets posed by 3D printing – Ganrty printer

2.3.1. Flowability

The flowability for polymer-modified mixes was measured in the exact same way as outlined in 2.2.1. The requirement for gantry printer mixes is that mixes have no spread: after the removal of the cone, the chunk of concrete must retain its shape and not spread to the sides. Therefore, the water reducer contents were adjusted for achieving this consistency. The example is shown in the Figure 6.

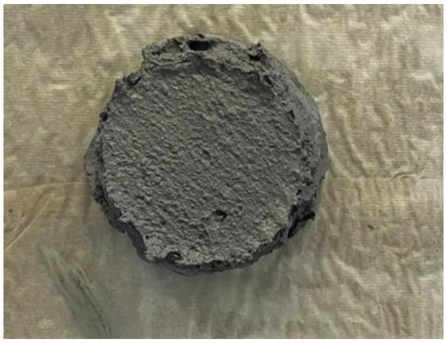

Figure 6: Flow of Polymer-Modified Mix

2.3.2. Pumpability

The pumpability requirement is not as strict for gantry printer mixes as it is for XTreeE printer since there are no hoses attached. The nozzle – the narrowest part of the extrusion head – is expected to be 1.5–3 inches in diameter and can be modified. This may allow the use of fibers in the mix, but the hypothesis must be verified in practice first. There are studies that evaluated changes to orientation of fibers due to extrusion process [3], and the same effects can be expected in this case.

2.3.3. Compressive and Flexural Strengths

The procedures for measuring compressive and flexural strengths of mixes are the exact same as outlined in section 2.2.3.

2.4 Printing Process and its Requirements

The printing equipment for the XTreeE printer consists of two mixers (green and blue), waste bin, and a pallet on which the printed structure is located during the printing procedure, as in Figure 7.

The printing process involves the setup and concrete printing stages. During setup, printer is calibrated and run raw without operation of pumps and printing materials to ensure that the nozzle draws the correct shape of structure intended for the print. After that, water is run through the hoses and the printer to ensure that there are no leaks in the system and the required pressures are established in each component. When the checking is finished, water is switched to concrete and the printer head is tilted around by 210 degrees to let the air out of the nozzle. This process can create a lot of waste and therefore requires additional concrete material and a waste bucket to prevent spills. Only after that the printing process begins.

Figure 7: Printing Setup

The green mixer is used for mixing the ingredients of the concrete, while the blue mixer is only used for maintaining the viscosity of concrete that is poured from the green mixer. From there, concrete is pumped along the hoses into the XTreeE extruder – head attached to the robotic arm, which then extrudes the material onto the pallet. An accelerator admixture is injected into concrete mix at the nozzle of the extruder in the volume of 5 mL per 1L of concrete.

The printing is done at the material extrusion speed of 2.2 liters per minute and linear speed of 187mm per second. The typical time period between extrusion of layers is 1-3 minutes for different structures. That is, it takes 1-3 minutes for the nozzle to reach the position right above the same position as on a layer before. This imposes a restriction on the allowable concrete setting time. The mortar should be able to stiffen quick enough for stable extrusion of layers to prevent unexpected spreading of concrete, and it should not stiffen too quick since this would result in weak binding of layers with each other leading to a compromised strength of a final structure.

For printing, mix M2 was chosen and scaled up to reach required volume. During the printing procedure, some of the HRWR prepared for mixing was not used, as well as around 400 grams of cement were added during the mixing process to reach the needed rheology of the mix. To evaluate flowability, on-site flow test was done with a target of 16.5 – 17.0 cm spread diameter.

The first printed structure completed in the study is a column with a height of 2m, cross section of 32 by 32 cm, layer width of 3cm , and 334 layers in total. In practice, due to waste of materials on setup, it was not possible to print the structure to its full height. As a result, the height reached was only about 1.5m.

The printed structure is left to cure. To prevent excessive cracking due to the consumption of water from the material in a hydration process, the exterior of the printed object is occasionally sprayed with water. This provides an additional source of water and limits the use of internal water resources.

2.5 Large-Scale Testing

After 4 days of curing, the printed column was prepared for large-scale testing procedure and placed under a hydraulic press. It was supported by 2 rollers 2 inches away from each edge of the lower wall of the column, as shown in Figure 8. Then, it was pressed from on the top in the middle by the press to determine force at which the column would break due to excessive deformation or due to layer tear-out.

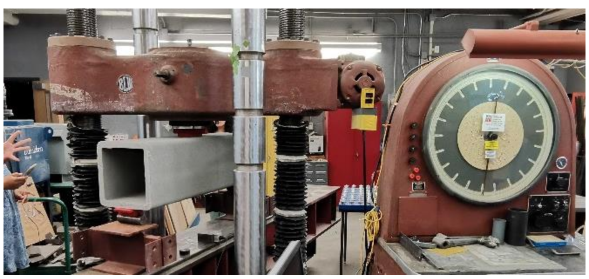

Figure 8: Large-Scale Testing Setup

3.Results

Table 2 presents the compressive and flexural strengths of chosen concrete mixes.

The 7-day compressive strength of mix M2 was measured to be 74.18 MPa, which is considerably lower than the standard for compressive strength of Ultra-High Performance Concrete [4]. The ASCE standard for 28-day compressive strength is 150 MPa [1], and it is unlikely that mix M2 will be able to reach it albeit it was not yet tested at older ages. However, the achieved compressive strength is much higher than 30MPa – required compressive strength of High-Performance Concrete (HPC) [5]. Therefore, the mix that was developed in this study truly qualifies for HPC. The flexural strength of 5.5 MPa is lower than that of other mixes that were developed during the study, 6.24 and 7.91 MPa for M1 and M3 respectively. Mix M3 was evaluated as not suitable for printing because it did not harden within 24 hours.

As for the polymer-modified mixes, all compressive strengths stand above 20.7 MPa – the goal value of the study. M_SBR3 has the measured compressive strength of 60.40 MPa that is lower than that of XTreeE printer mix. However, that is the highest achieved compressive strength among the developed polymer-modified mixes. Furthermore, flexural strength of the mix is much higher than those of M_SBR1 and M_SBR2, so mix M_SBR3 will likely be used for gantry printer printing.

Mix #	Compressive Strength (MPa)	Flexural Strength (MPa)
M1	79.80 ± 6.40	6.24 ± 0.63
M2	74.18 ± 1.00	5.54 ± 0.88
M3	81.80 ± 2.67	7.91 ± 0.13
M_SBR1	27.59 ± 0.22	4.34 ± 0.52
M_SBR2	21.82 ± 2.50	4.82 ± 0.40
M_SBR3	60.40 ± 1.19	6.75 ± 0.35

Table 2: Compressive and Flexural Strengths of Printing Mixes

During large-scale testing, the printed column cracked on one of the lower edges, which led to the failure. The load applied to the column at the moment of failure was 1.84 kips at the displacement of 0.244 inches. The Figure 9 depicts the broken column specimen, and Figure 10 provides the load vs displacement graph.

Figure 9: The Broken Specimen

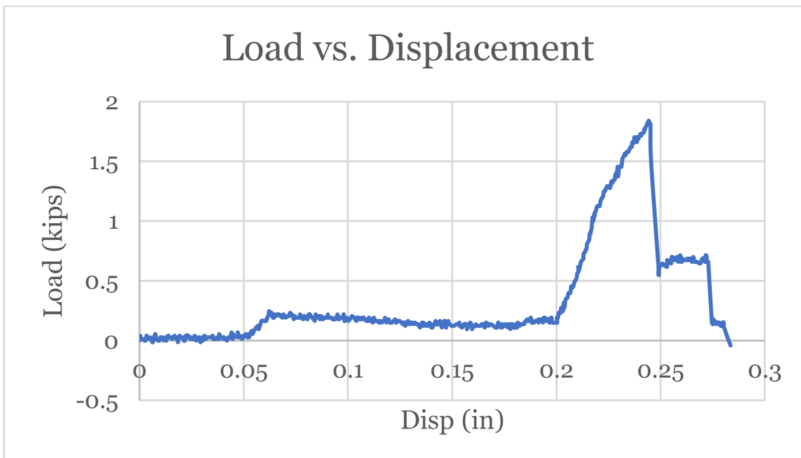

Figure 10: Load vs Displacement Graph for Large-Scale Test

4. Discussion

The goal for compressive strength of XTreeE printer mix was not reached, yet the result is satisfactory since the measured compressive strength is close to the upper boundary of the range of compressive strength of HPC. It can be increased using the accelerator admixture that is injected at the nozzle of the extruder. Our tests on other mixes showcased that accelerator contributes to compressive and flexural strengths of concrete mixes at 7 days of age. Therefore, higher strength of printed structures can be expected.

Preparing samples in mold has several limitations in estimating the true strength of a printed structure since the condition of sample preparation are different from on-site conditions. From concrete is 3D printed, there are no walls to limit its flow, which is not the case for plastic cylindrical and rectangular metal molds used in the study. Therefore, extracting samples from the actual print could provide more accurate results on the compressive and flexural strengths of concrete mixes.

As for large-scale testing, since the column specimen broke on the edge where concentration of loads is higher than in the middle sections, it can be evaluated that the bond strength was high enough to prevent tear-out failure in the middle point where the load was applied from the hydraulic press.

5.Conclusion

The study covers the process of 3D printing, large-scale testing of printed structures, and development of concrete mixes for the operations of Cornell University Bovay Laboratory Complex. Furthermore, it outlines some important considerations to be made to avoid few of the mistakes during the printing process and allows further studies in the areas of 3D concrete printing. Particularly, some of the future goals involve printing walls, staircases, and beams to investigate the possibility of using 3D printing of concrete in structural applications.

The important conclusions drawn from the printing process are related to the material use and material availability at the printing site. The experience shows that additional materials should be kept at the mixing station to ensure quick response to unexpected properties of a mix due to differences in mixing technique, such as mixing speed, the surface area of walls and blades, and other parameters. This would allow to add the lacking ingredient without significant changes to intended mixing procedure. The materials should also be present in excess to constitute for waste during the process of setup process.

6.References

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