Digital Fabrication and Mechanical Properties of 3D-printing Concrete

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Abstract. 3d printed concrete technology is a hot research topic in the field of architecture. Printed by layers, the concrete could be stacked accurately in the shape which is digitally designed on computer programs. However, the conventional cement mortar is not suitable for 3D-printing, Because that its aggregate ingredients may cause the cracks in the process of printing. Moreover, the buildability and rheological properties of conventional mortar cannot reach the requirements of 3D-ptinting concrete technology. Ultra-high performance concrete is a developing category of material used in concrete structures and it is considered to be one of the most appropriate printing materials. As the popularization of computer technology, it is a necessary task to research on the digital construction way of concrete structures. And 3D-printing concrete technology combines the popular topics above together. This study mainly introduces the fabrication process of ultra-high performance concrete and digital printing process of 3D-printing concrete, and the mechanical properties of printed specimens are studied by the experimental results.

Keywords: 3D-printing Concrete, Ultra-high Performance Concrete, Mechanical Property.

1. Introduction

Concretes are cement based composites, which takes cement as cementing agent, takes sands and rocks as aggregates, and takes additives as admixtures. As for its excellent properties including low-costing, durability, fire prevention, concrete has become the most widely-used building material. At the same time, the conventional reinforced concrete has heavy self-weight, requires inconvenient templates, and requires a large number of labors, which hinders its further development. And 3D-printing is an emerging technology. Authors have paid efforts in applying the cutting-edge digital technology in conventional concrete fabrication and they have achieved some breakthroughs, the 3D-printing concrete(3DPC) technology. By printing concretes, manufacturers are able to design the structure conveniently by simply modeling it in computer software and then print it by squeezing out mortars. In this way, the template is no more needed and concretes can be stacked into varieties of shapes, not just squares and circles. These are the main benefits of digital 3DPC.

Since the 20th century, construction structures have developed to be higher, longer, and more durable, which demands the strength of concrete to develop as well. In 1970s, concrete with its compressive strength higher than 60MPa (High Performance Concrete, HPC) is invented and get wide application in civil engineering. During 1972-1973, Brunauer published his essay, Hardened Portland Cement Pastes of Low Porosity, on journal Cement and Concrete Research, which first reported cement-based material with compressive strength higher than 240MPa. And in 1994, Larrard first raised the concept of UHPC, which means ultra-high performance concrete.

The basic point of 3DPC technology is to apply the computer-aided design tools in the process of construction. In this case the intellectualization could be accelerated, the construction time could be shortened, and the efficiency could be improved. Researches have proved that for the construction of complex structures, 3DPC technology is better than the traditional construction form both in cost and efficiency. Wangler et al. [1] also believe that with the increase of structural complexity, 3DPC technology will have more and more prominent advantages in terms of construction cost and market share, because in the traditional construction process, the increase of structural complexity will cause the increase of cost and time in formwork making and pouring process. 3DPC technology does not need template assistance in the whole construction process, and has unique advantages in the forming

process of complex structures. On the other hand, the worldwide population aging phenomenon would further increase the labor cost, which is of great focus in construction industry and the cost expenditure of conventional construction methods. It can be expected that digital 3D printing construction technology will have considerable development in the future.

2. Connection between UHPC and 3DPC

According to different material forms and process modes, 3DPC technology is basically divided into 3 categories: (1) mortar-squeezing based stacking 3DPC tech; (2) powder-bonding based 3DPC tech; (3) spraying-based stacking 3DPC tech. For digital 3D-printing concrete, the mortar-squeezing based stacking mode is a relatively proper choice because compared with powder-bonding and spraying, squeezing out the mortar can best shape the concrete structure as modeled on computer, which means it is a more accurate method with marginal error. As a result, present 3DPC is realized mostly by squeezing out mortar. The size of nozzle limits the particle diameter composed in the mortar. When aggregate size is too big, nozzle could be blocked, and when its size is too small, aggregate's surface area extends, which requires more amount of mortar to cover the aggregate, leading to the concrete cracking more easily. In a nutshell, problems faced by 3DPC tech includes: (1) difficult to reinforce; (2) difficult to use coarse aggregate; (3) difficult to ensure the bond strength between layers as 3DPC is structured in the shape of layer by layer.

At this point, authors have regarded UHPC as the ideal material for 3DPC: (1) Coarse aggregate is hardly added into UHPC; (2) UHPC has incredible compressive strength and excellent durability; (3) UHPC's cementitious particle size is small, strengthening its bonding strength.

3. Fabrication method

Through the study on conventional cement-based concrete over the years, researchers have realized that as a porous heterogeneous material, concrete's strength is largely decided by its pore structure. Also, it is important to stack micro-particles densely to get ultra-high performance. Main ways to fabricate the UHPC includes: (1) Remove coarse aggregate and limit the maximum particle size of fine aggregate to no more than 300μm. In this way the uniformity of aggregate is improved; (2) By optimizing the gradation of fine aggregate, the whole particle space is densely distributed, and the compactness of aggregate is increased; (3) By adding silica fume or fly ash as ultra-fine active mineral admixtures, it has a good micro powder filling effect, reduces the porosity and pore diameter through chemical reaction, and optimizes the internal pore structure; (4) By adding short and fine steel fibers(more research will appear in subsequent post), the ductility of the material improves.

3.1 Material composition and mix proportion

Like the research of other concrete materials, the research of UHPC starts from material preparation. Researchers from various countries have carried out a large number of mix design in combination with local materials, and Chinese researchers have also carried out a lot of researches [2-7].

Yigiter H et al. [8] carried out the research on reactive powder concrete(RPC) with low cement dosage. Fly ash replaces 60% of cement, and the pressure was applied in the process of setting and hardening to obtain 338MPa RPC. Using fly ash and slag instead of silica fume and cement in RPC decreases the amount of superplasticizer and reduce the hydration heat and shrinkage of RPC. Palm oil putty is used to replace 50% of cementitious materials [9]. The compressive strength, flexural tensile strength and direct tensile strength of prepared UHPC is 158.28MPa, 46.69MPa, and 13.78MPa, respectively. Sometimes researchers use rice husk ash to take place of silica fume. Under the standard curing system, UHPC with strength more than 150MPa can be prepared. When researchers use cement + 10% silica fume + 10% rice husk ash, the performance of UHPC is the best.

In the setting and hardening process of RPC, the addition of partially hydrated cement-based material (PH-CM) can promote the hydration of cement and make RPC have high early strength.

3.2 Mixing and curing method

Different from ordinary concrete, RPC is easy to agglomerate in the mixing process due to the mixing process of matrix material, fine-grained component material, and steel fiber, which affects the homogeneity and material properties of RPC molding. Scholars have carried out corresponding research on the mixing equipment to be used, the mixing time and the sequence of the mixture. For example, the research of Arunothayan et al. [10] shows that the working performance of RPC with water reducing agent added after mixing for 1 min is better than that of RPC with water reducing agent added immediately . Besides, test results show that different feeding sequences have a certain impact on the flexural strength, tensile strength and compressive strength of RPC, especially on fluidity of RPC [11].

High-temperature and high-pressure curing system is an important means for UHPC to obtain high performance. The higher the temperature and the longer the time, the more silica fume participates in the reaction and the denser the internal structure is. YANG S L et al. point out that compared with 90 ℃ thermal curing, the fracture energy, compressive strength, and flexural strength of UHPFRC test block under 20 ℃ standard curing condition are reduced by 20%, 10% and 15% [12]. Measuring the hydration degree of cement, silica fume, quartz powder and other cemented powders under different curing conditions by the way of Si magnetic resonance method (Si NMR), an effective and economical curing method is established[13]. Richard et al. [14] shows that 90 ℃ thermal curing can accelerate the pozzolanic reaction and change the microstructure of hydrate formed. High temperature curing (250 ℃ ~ 400 ℃) can promote the formation of crystalline hydrate and the dehydration of hardened slurry. Arunothayan et al. [15] shows that compressive strength of RPC specimens can reach 500MPa after curing at 50MPa and 400 ℃ for 48h. Cheyrezy et al. [16] analyzed the micro structure of traditional RPC under thermal curing using thermogravimetric analysis and X-ray diffraction. It is considered that the porosity of traditional RPC is the smallest when the curing temperature is between 150 ℃ ~ 200 ℃. For curing ways, Cheyrezy carried out Comparative tests on four curing ways: steam curing, lag steam curing, cooling steam curing and conventional curing. The results show that steam curing has the greatest impact on wood properties, while steam curing, lag steam curing and cooling steam curing have less impact on wood properties [16]. Steam curing can increase the tensile strength, compressive strength and elastic modulus of materials, reduce creep, accelerate shrinkage speed and improve impermeability. However, steam or autoclave curing brings difficulties to construction and increases the preparation cost, which demands more careful consideration on the choice.

The pressure during curing also affects the performance of UHPC. Research results show that the flexural strength and toughness of RPC increased by 34% ~ 66% and 3.39 ~ 4.81 times when the preload of 5 ~ 25MPa is applied in the condensation process [16]. This is because the preload can eliminate pores and free water and make the particles more compact. Steaming time, temperature and pressure will affect the performance of RPC; For each pressure and temperature, there is a critical autoclave time; Too long steaming time will reduce its mechanical properties.

3.3 Mortar preparation

Arunothayan et al. [15] introduced one specific mixing process to obtain printable UHPC mortar: All mixing processes follow the same mixing scheme. Researchers first mix OPC, silica fume and sands, which are dry materials, for 3 min in a 60 L container. Then researchers pour water into the container gradually and mix them for about 5min. After that, researchers mix the HRWRA with remaining water gradually. The process suspends when reaching the expected rheology. For fiber reinforced mixtures, researchers gradually add fibers into the mixture and mix them for about 6min. examiners visually check the fiber dispersion in the mixture. For the last step, researchers gradually add some nano clay to adjust rheological properties in purpose of making the mixture suitable for printing.

3.4 Printing stage

A gantry-type 3D printer is the most widely-used machine in the study of 3DPC technology. As it is for printing specimens on a table, which means the size and volume of the printer is limited, researchers have adopted an effective workspace of 1.8m(L) x 1.6m(W) x 1.8(H) [15]. While the printer size is basically fixed, its nozzle diameter, which largely influence the printing quality, the printing velocity and the bind between layers of printed specimens, is alternative. Nozzles are mounted to the actuator. One of the concentrations of this study is the digital fabrication of 3DCP. Therefore, the nozzle's triaxial movement is controlled by a mechanical arm, which moves as researchers command through a customized computer program. A customized mortar feeder connects the extruder inlet and the mortar holder, which simplify the process of adding printing materials. All the customized components are 3D printed.

4. Mechanical properties

4.1 3DP-UHPC under triaxial compressive test

4.1.1 Specimen type

Arunothayan et al. [17] carried out this experiment. Figure 1 shows the desktop 3D printer used in this experiment. The diameter of extruder is set to be 15mm, and the printing layer height is primarily set to be 5mm, which collectively considers factors of extruding velocity, nozzle diameter and nozzle moving velocity. The mixing process of printing materials can be divided into 3 main steps [17]: (1) first mix the cement, silica fume and fly ash, which are cementation materials, with nano

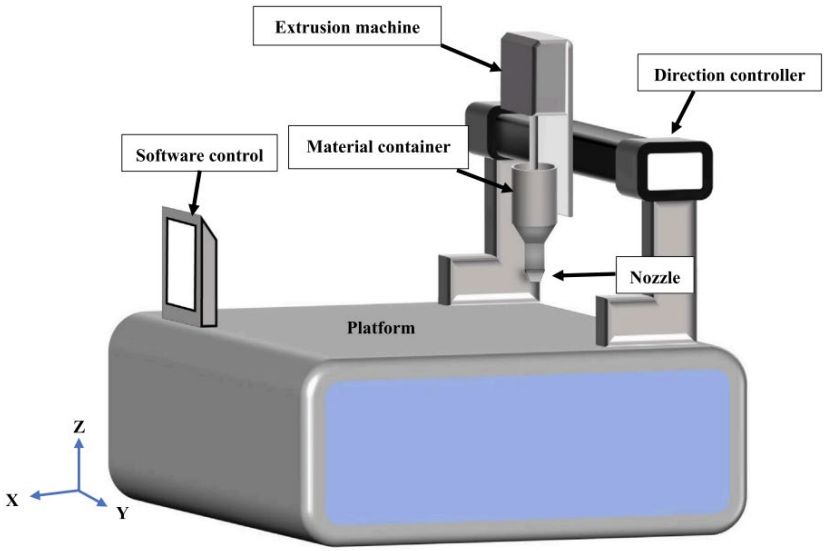


Figure 1. Desktop 3D printer diagram [17]

calcium carbonate (NCC), arenaceous quartz and cellulose in the mixer. Then researchers dry the mix for about 4 min. (2) second mix about 10kg of PS(polycarboxylate superplasticizer, PS) with about 52L of water, compared with PS, then researchers have them wet mixed for 4 min. (3) put the remaining 102L of water in the mixer, and wet mix for 4 min. After that, researchers move the mortar into the material holder which is connected with the extruder inlet. To achieve ideal printing thickness, the extruding speed of the nozzle is set to be 5mm/s, the moving speed of the extruder is set to be 15mm/s, and the time break between printing layers is set to 17s. The printed cubic brick is of 60mm x 110mm x 250 mm and contains 22 layers. To get proper specimen to have triaxial compression test, three cylinder-shaped specimens are drilled from every one brick by the way of coring. The diameter and height of cylinders is 50mm and 100mm, respectively. The printed cubic brick and the drilled cylinder is shown in Figure 2. More printed specimens of this size are obtained in the same way. Meanwhile, a mold-casting concrete cylindrical specimen of this size is obtained to compare with the

printed ones. For both mold-casting and printed cylinder-shaped specimens, the dimensional error of each specimen is limited to ± 1mm.

4.1.2 Test scheme

(1) First researchers put the specimen on a cushion cap, over which is a servo-controlled hydraulic actuator (SCHA), and below which is a linear variable differential transformer (LVDT) (both shown in Figure 3). SCHA is used to control compressive stress during the test and LVDT is used to measure the deformation in Z direction of the cylinder.

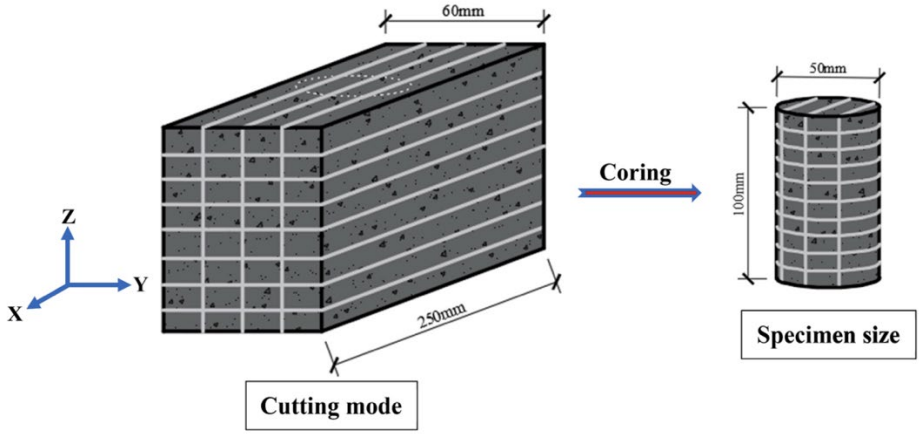


Figure 2. Diagram of 3D-printing specimen in confining compressive test [17]

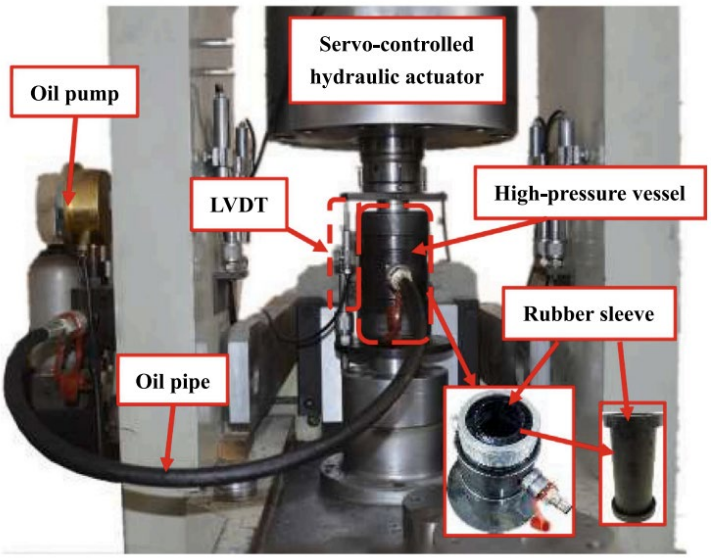


Figure 3. Triaxial test equipment [17]

(2) Then researchers apply loads on the specimens. And this process can be seperated into two stages:

First, at start, the confining stress (horizontal stress, $\sigma_2 = \sigma_3$) and compressive stress (axial stress, σ_1) are loaded at the same time, and the loading rates of all of them(σ_1, σ_2, σ_3) are the same(force control with the rate of 0.5MPa/s). The confining stress σ_1 keeps increasing until it reaches the target pressure f_r, which means at this time $\sigma_1 = \sigma_2 = \sigma_3 = f_r$ and σ_2, σ_3 no longer increases.

Second, as long as confining pressure reaches the target, the confining stress no loner increases, and since which, the mode of applying loads is displacement control with the rate of 0.5mm/min. The maximum value of axial stress is f_{cc}.

4.1.3 Test results

Table 1 shows the failure modes of mold-casting cylinder specimens and 3DP cylinder specimens in the condition of different peak confining pressures. Figure 4 compares test curves of mold-casting

and 3DP specimens to figure out their contrast of the compressive toughness, together with 3DP-UHPFRC, which will be talked about later.

Table.1. Picture of two kinds of specimens when failing [17]

Confining pressures						
Types of specimens	0Mpa	5Mpa	10Mpa	20Mpa	30Mpa	40Mpa
MC-UHPC						
3DP-UHPC						

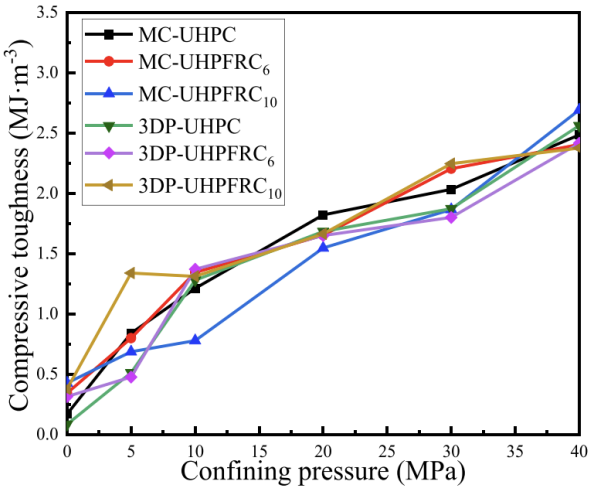


Figure 4. Compressive toughness curves of mold-casting and 3DP specimens under different confining stress[17]

According to test statistics, 3D-printing concrete specimens performed similar peak-bearing stress and compressive toughness to conventional mold-casting concrete specimens, which means innovative construction methods to print concrete actually barely influences the strength of concrete, or reinforced concrete. Considering the relatively weak strength between layers of the printed specimens, this result is encouraging. However, this also indicates that the triaxial compressive test is not enough to assess the practical application of 3DPC, more tests such as shear tests are required.

4.2 3DP-UHPC under shear test

Direct shear test is more usually applied in soil mechanics. It is convenient and cost the least time but cannot figure out where the failure would occur. For 3DPC, obviously the weakest part of a specimen is the section between layers, which means this is a pre-determined shear plane. For this reason, this test is suitable for measuring shear strength of 3DPC. Hailong Wang et. al[18] carried out this experiment.

4.2.1 Test equipment and scheme

The specimens used in this test are printed cubic bricks and mold-casting circular bricks both with the diameter of 72mm and the height of 25mm.

An automated machine named Shear Trac II is applied in this shear test, while internal diameter and internal height of the circle-shaped container is 72.5mm and 42.7mm, respectively. Equipment picture is shown in Figure 5.

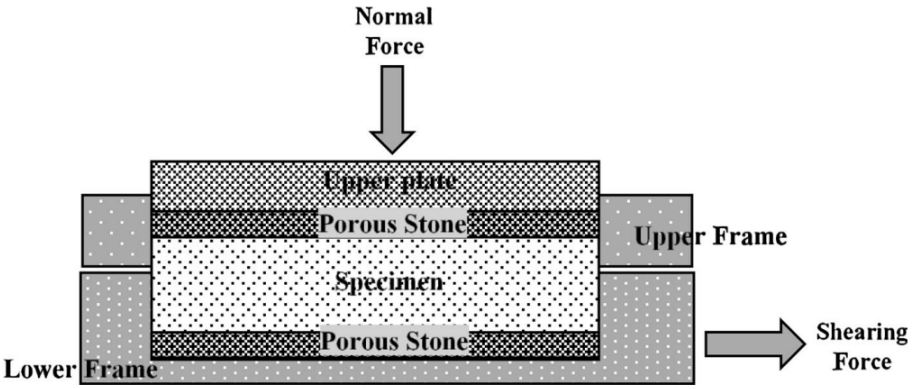


Figure 5. Schematic diagram for a typical direct shear test [18]

Specimens are shaped into cylinders and then placed into the container in three layers in order to avoid pores within interfacial region, which is the pre-determined failure section. Before applying loads to shear the specimen, lubricant oil is added within the shearing surface of the metal container to make sure the friction force is generally small enough to ignore. For the same reason, the container should be marginally lifted before starting the shear test.

In the process of shear test, the displacement rate and normal stress are limited to be no more than 15mm/min and 15kPa, respectively. As the scheme of this test is basically classic direct shear test which is widely used in the assessment of soil shear strength, more specific test details are not included.

4.2.2 Test results

Shear strength, layer interface, and strip interface of test results are given by drawing curves in Figure 6.

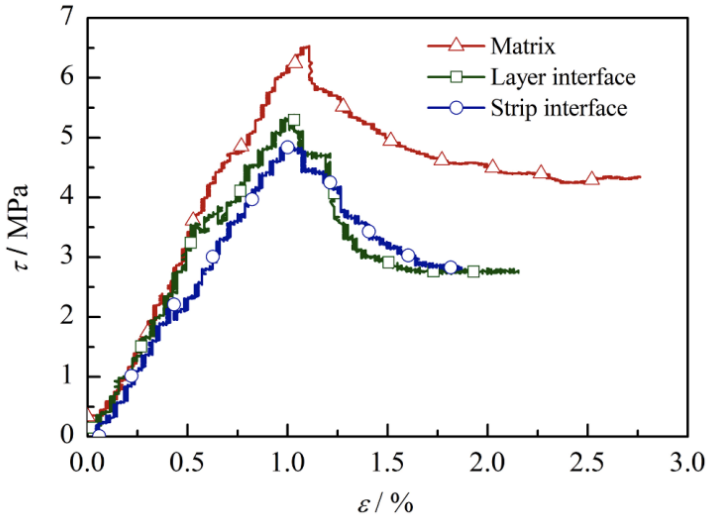


Figure 6. Shear (τ)-strain (ε) curves[18]

As hypothesized, the shear strength on the layer interface decreases compared with that of the matrix, but not that significantly. But the curve indicates that on the layer interface, the ductility decreases, which means brittle failure occurs when shear stress excesses the yield stress of the 3D

printed material, cracks extends largely and the whole structure fail in a short time without any previous alarm, leading to interlayer slips or other possible failure mode. However, considering that concrete structure is usually used to bear axial loads, relatively weak strength in a certain direction is not that precarious. Also, further study on ways to strengthen the bonding shear strength between layers has been reported. Therefore, the prospect of 3DPC is predictably prosperous, despite its existing problems.

5. Conclusions

(1) The compressive strength of 3DPC is slightly weakened compared with that of mold-casting concrete in vertical direction to printing plane, which indicates that 3DPC is a possible alternative.

(2) The shear strength of 3DPC between layers is 15.38% less than that of mold-casting specimens, which requires engineers to design more optimized structures.

(3) UHPC is a relatively realistic material for 3DPC technology mainly for it hardly contains coarse aggregate.

(4) Digital fabrication is one of the benefits of 3DPC. Experiments included in this study indicates the accuracy and efficiency of 3D-printing a concrete structure.

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