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Evaluations of 3D Concrete Printing Produced in the Environment of United Arab Emirates

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***Abstract*—**3D concrete printing is one of the most innovative and modern techniques in the field of construction that achieved several milestones in that field for the following advantages: saving project's time, ability to execute complicated shapes, reduce waste and low cost. However, the concept of 3D printing in UAE is relatively new where construction teams, including clients, consultants, and contractors, do not have the required knowledge and experience in the field. This is the most significant obstacle for the construction parties, which make them refrained from using 3D concrete printing compared to conventional concreting methods. This study shows the historical development of the 3D concrete printing, its advantages, and the challenges facing this innovation. Concrete mixes and materials have been proposed and evaluated to select the best combination for successful 3D concrete printing. The main characteristics of the 3D concrete printing in the fresh and hardened states are considered, such as slump test, flow table, compressive strength, tensile, and flexural strengths. There is need to assess the structural stability of the 3D concrete by testing the bond between interlayers of the concrete.

***Keyword*—**3D printing, concrete mixes, workability, compressive strength, slump test, tensile strength, flexural strength.

I. Introduction

THREE-dimensional (3D) printing, also known as additive manufacturing, was initially used in car assembly and ventures, which began in the mid-twentieth century. Since then, its applications have expanded, including therapeutic, aviation, and construction businesses. In processes that require extensive work, such as buildings and scaffolds in the field of construction, the robotic and fast nature of 3D printing is useful, and is being developed further due to its cost efficiency aspects In the last decade, Khoshnevis [1], a professor at the University of Southern California, developed a 3D printing housing structure known as "Contour Crafting". This method enables the 3D printing of concrete structures that integrate the essential channels for electricity, drainage systems, and conditioning. Khoshnevis' method is considered a possible solution for lowering the cost of housing in low-income countries, and also for collaboration with NASA's Advanced Concepts (NIAC) program to building housing in space [1], [2]. Furthermore, a 3D printer based in San Francisco, by a start-up company called Apis Cor recently exhibited that it could 3D print concrete walls for small houses within a day or less, indicating the time-saving implications of 3D printing. 3D printing is not only being used in the construction of houses but also in building bridges, for example in Spain [3].

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Following the international success of 3D printing in the field of construction, the United Arab Emirates (UAE) recently built a fully functional 3D-printed structure in Emirates Tower, Dubai, as part of the Dubai strategy. This strategy focuses on three main sectors: construction, medical products, and consumer goods. The office integrated a unique building design and 3D printing technology to offer essential services within the building, such as electricity, water, telecommunications, and air-conditioning. It took 17 days to print, and two days to implement. The development process of the office did not only save time but also cut the cost of labors working on the project. This is because 3D printing requires only one supervisor to monitor the function, seven employees to install the parts of the building, and ten engineers and specialists. The unique mixture of cement used in the printer was transported from the United States and was tested carefully by China and England to ensure its safety for use in construction.

3D printers work by first laying down a thin layer of dry powdered concrete mix. Then, an image of one slice of the 3D object is sprayed onto the dry mix by using an inkjet. The wet parts of each layer hydrate into the hard-rock concrete and the rest remains in a powder form to be brushed off later. The process of laying the concrete down is repeated until a solid object is built. The dry concrete mix acts as a support structure during the printing process. Finally, after curing the concrete, which usually takes approximately 12 hours, the object can be lifted out of the powder bed, and the dry mix used to support the concrete can be recycled [4].

According to Rael and Fratello, in 1756, Smeaton rediscovered concrete by mixing hydraulic lime and powdered brick as aggregate. These mixtures produced concrete with a comprehensive strength comparable to the combinations being used today [4]. The mixes that are most frequently used include Portland cement, water, and aggregates. Hence, concrete is the core building material used in construction, with cement as one of its main components. In order to make cement, coal burning is needed, which is ranked amongst one of the highest energy exhaustive productions [5]. Coal also emits a significant amount of carbon dioxide gas into the environment. Through 3D printing, civil engineers can achieve a more environmentally friendly, inexpensive, and time efficient, process of construction whilst maintaining specific design and shapes, which is not possible via traditional techniques. 3D printing serves the environmental industry in being more sustainable and effective by using only the amount of materials needed for construction and cutting down waste.

Civil structures are large-scale, with an area of acres, and are subjected to complex loadings including dead, live, wind, and seismic, amongst others. Because of this, there are some limitations and hurdles to overcome in order to efficiently use 3D printing in this field. One example is to determine the right 3D concrete mixture that can be extruded efficiently through the nozzle [6]. Secondly, to 3D print, a structure; concrete should be used with maximum compressive strength and workability, and minimum water content, which is a hurdle to overcome [7]. Thirdly, the size of the nozzle from which the concrete will flow plays a critical role as a small sized nozzle can stop the material flow, creating gaps and inconsistency in the project.

The aim of this paper is to address the ability of 3D printing and the creation of eco-friendly houses. This article will mainly be based on secondary and primary research in which interviews, journals, research papers, reports, books, and study cases available in the American University of Sharjah library will be utilized to collect information for the project.

II. Updated 3D Printing Technology

The process of 3D printing is applicable for conventional structures, including building and scaffolds, which require extensive work. Starting up, in 1995, the idea was of forming cement-using steam for the connection of materials in layers. The other method is called contour crafting, which is based on shaping method and ceramic extrusion. The research of 3D printer is developing in the construction areas. In addition, the materials used in the 3D printers are tested carefully to make sure that they are safe for construction. The printing process is a digitally controlled process of manufacturing architectural and structural components without formwork, unlike the traditional construction method. Hence, it is developed until it reached a requirement of only one supervisor to monitor the function, few numbers of employees to install the parts of the building, engineers, and specialists.

III. Evaluation of the Local Materials Used in 3D Printers

During the progress of the project, we need to identify the availability of local materials for the 3D printer. There are various types of cement that can be used in the project however it depends on their properties. Types of cement are the following: rapid hardening cement, low heat cement, quick setting cement, sulfates resisting cement, air entraining cement, high alumina cement, and other types. In this project, cement type will be chosen depending on the project's requirement to produce a mixture with good properties.

The properties of suitable cement are the following: moisture resistance, strength and durability, affordability, and fire resistance. There are several types of aggregates that influence the character and performance of the concrete mix such as, shape, size, texture, voids, absorption and surface moisture, moisture content, unit weight, abrasion and changes in gradation. The shape of aggregate and its surface texture mostly affect the properties of freshly mixed concrete. Smooth, rounded compact aggregate requires less water to produce workable concrete than rough, angular, and elongated particles. Void content between aggregate particles affects the amount of cement past needed for the mix. For instance, angular aggregates increase void content. Absorption and surface moisture is measured when choosing aggregates because the inner assembly of aggregates is made of solid materials and voids that may be filled with water. Thus, the amount of water in the concrete mix is advised to be regulated in order to include the moisture condition of aggregates. Abrasion is very important to take into consideration when aggregates will be used in pavements and heavy-duty floors. Stiffer aggregates can be used in highly abrasive situations to reduce wear. In addition, the availability of chemical admixtures is highly effective in concrete mixes in addition to its basic constitutes: cement, water, aggregates, and sand. Superplasticizers are chemical admixtures that substantially improve workability and level on the consistency of a given water-cement ratio by reducing the amount of water 12% to 30% [4]. Moreover, fibers can be used in mixes in order to resist cracks that are caused by shrinkage in the surface layer of concrete. The main purpose of fiber is to create a stronger concrete and increase ductility, increase durability, and eliminate cracks that are due to the reduction of volume. Viscosity modifying admixture helps improve the extraction of fresh concrete through the nozzle and maintains its homogeneity. It will also control the segregation of the extruded concrete. Micro-silica develops two functions in concrete: firstly, it acts as filler by decreasing the average size of pores in cement paste and secondly it provides a constant distribution and better volume of hydration products.

IV. Characteristics of the 3D Concrete Printing

When it comes to 3D printing concrete mix, it is very important to design mix that enables to balance concrete pump-ability and build-ability. The concrete blend for 3D printing is the foundation part of the technical aspect that will be pumped through a small nozzle. The concrete mix must be intended to meet specific essential criteria that have an immediate association with the strategy of printing the mix. Consequently, it is fundamental to guarantee a correlative connection between the design of the mix and 3D printer. With a specific end goal to achieve the ideal combination, specific scientific objectives are set for the mixture.

Fig. 1 depicts the characteristics of the 3D concrete mixture. It illustrates the complexity of producing appropriate 3D concrete mixture. For instance, maximizing the compressive strength of the mix means minimizing the water-cement ratio. However, certain water content must be maintained to ensure appropriate workability of the concrete. In addition, the mix in the system must be flowable and at the same time can set quickly to support multi layers. Thirdly, when poured, the mix should set as fast as possible but not fast enough to ensure appropriate bonding with the subsequent layer. Finally, it should take minimum construction time and on the other hand it should not compromise on sustainability. In order to address these goals, specific measurable criteria of the mix should be set.

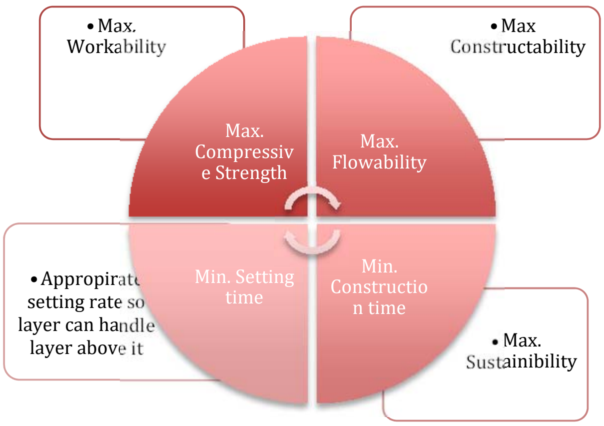

Fig. 1 Challenges for 3D Printing Concrete Mix

The four most important aspects of the mix studied are flowability, constructability, compressive strength, setting time. Flowability is 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. Constructability 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, setting 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 fresh concrete must have a certain flowability upon its transfer that must not threaten its ability to stiffen upon pouring. Aggregates of a maximum size of 2 mm should be selected so that the mix can pass through the nozzle with consistency [1].

V. Concrete Mixes and Materials for the 3D Printing

In order to achieve optimum efficiency while using concrete mix design in 3D a printing mixes in Fig. 2 are used.

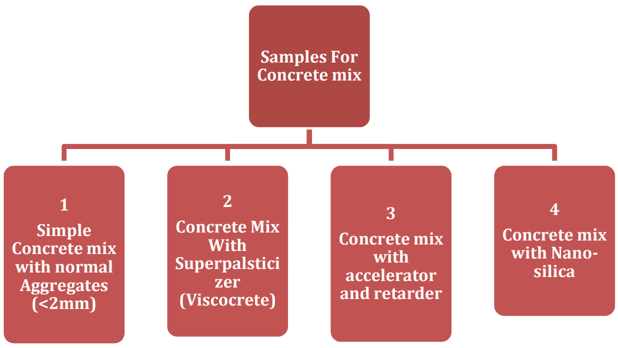

Fig. 2 Samples for 3D Printing Concrete Mixes

A super-plasticizer (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 [7]. In addition, a retarder is also added to prevent the concrete from settling early in the tank.

Nanoparticles have a high surface-area-to-volume ratio. In this way, nanoparticles with 4-nm diameter have more than 50% of its atoms at the surface and are thus very reactive. Therefore, the use of nanoparticles in mortars and concretes significantly modify their behavior not only in the fresh but also in the hardened conditions, as well as the physical/ mechanical and microstructure development [8]. An appropriate balance of all the constituents has to be reached to ensure proper functioning of the mix.

VI. Evaluation of the Fresh Concrete Properties

In order to characterize the printing mixtures, the unit weight and flow should be measured. Flow of each mixture is determined using a flow table (ASTM C1437-15 [9]), where initially a mold is filled with mortar and compacted. Then the mold is lifted away from mortar and the table is immediately dropped 25 times in 15 s. The flow is the resulting increase in average base diameter of the mortar mass, expressed as a percentage of the original base diameter. Print quality is the properties of a printed layer such as surface quality and dimensional conformity/consistency. A printing mixture could be considered acceptable when the three following requirements are satisfied: printed layer must be free of surface defects, including any discontinuity due to excessive stiffness and inadequate cohesion, the layer edges must be visible and squared, dimension conformity and dimension consistency must be satisfied by printed layer.

There are five concrete properties that should be taken into consideration while progressing the 3D printer project in construction which are the following: consistency, workability, settlement and bleeding, plastic shrinkage, and slump loss. The consistency of concrete mix is very significant since it measures the stiffness and fluidity of the mixture during compaction and supervision of concrete. Slump test is frequently used to measure the consistency of the mix. The equipment used in this experiment is slump cone, base plate, measuring scale, and tamping rod. This test is very significant for all the different five mixtures to be used in the 3D printing. To start up the procedure, first, the slump cone is placed in the base plate. Then the cone is filled by concrete in four layers, each time filling should be equal to one-quarter of its cone's actual height and should be tamped 25 strokes by the tamping rod in a constant manner. After tamping the last layer of concrete, it should be to the level of striking off by using a trowel. The second property is workability of concrete mix that determines the ease of placement and compaction. Workability affects strength and durability of the finished product. Concrete mix samples with same consistency do not mean they have the same workability. For this reason, factors affecting workability are the following: humidity, methods of placement and transmission of concrete, aggregate distribution, water-cement ratio, properties of cement, nature of aggregate particles, and temperature of concrete mix. The concrete property can be improved by increasing the water-cement ratio, size of aggregate, increase mixing time and the use of rounded and smooth aggregates. The slump test is also used for checking the workability of freshly made concrete. In addition, another important test for the project is the compaction factor test and vee-bee consistometer that can measure the workability. Compaction factor test is the required amount of work needed to compact the concrete to its maximum density. Vee-bee consistometer is used for dry concrete that has very low workability.

The third property of fresh concrete is bleeding and segregation. Since cement and aggregates have three times larger densities than water, bleeding is the segregation of water in concrete that tends to rise on top of the fresh material. Excessive bleeding is problematic since it affects durability. One of the main reasons behind excessive bleeding is high water-cement ratio. The aim in creating the concrete mixes for the project is to manage the bleeding in order to guarantee good quality of concrete. Bleeding can be controlled by using finer cement, decreasing water content, increasing fine aggregate, using air entraining admixtures and supplementary cementitious materials.

The fourth property is plastic shrinkage, which is the shrinkage in the volume of concrete by the same amount of water elimination from compaction of concrete before it sets. This property must be taken into consideration since it may cause cracks in the surface of the fresh concrete. The last property that should be taken into consideration is the slump loss, which is the reduction in a slump from the time of mixing until discharging it to the delivery vehicle. In order to control the slump loss the following methods should be done: ensure low temperature, usage of retarders, usage of plasticizers, and ensure initial high slump.

VII. Evaluation of the Hardened Concrete Properties

The tests on hardened concrete are extremely important because it gives us a measure of how much load will a structure sustain or bear before failure and thus ensuring safety for the building and people by not exceeding the limit.

There are three tests of Hardened Concrete:

A. Compressive Strength Test

One of the most valuable properties of concrete is strength. The values we usually obtain depend on the dimensions and shape of specimens, batching, mixing, method of sampling, temperature, moisture conditions during curing and other sources that may affect the behavior of a specimen. Hence, the two methods used in civil engineering department to determine compressive strength are destructive (cube, cylinder, and beam), and non-destructive.

The equipment used for the destructive compressive strength test are:

1. Compression machine.
2. Cylinder molds.
3. A sample of concrete. (cubic concrete, cylindrical concrete, beam concrete)

With following the procedure:

1. Prepare the samples. “Cubic, cylindrical, and beam concrete”.
2. Record the dimensions of each concrete sample.
3. Test the specimens after taking the measurements in a moist condition.
4. Put the sample in the compression machine.
5. Record the maximum load of the specimen during the test.
6. Repeat the steps for each specimen and find the maximum load.
7. Find the compressive strength of each specimen.

The Non Destructive method includes:

- Rebound Hammer
- Ultrasound (to determine the uniformly, cracks, voids, density, strength)
- Core meter (to locate the rebar)

This test is also known as Schmidt hammer or impact hammer to test the concrete. This test is based on showing that the elastic mass's rebound depends on the hardness of the surface against which the mass impinges. This is achieved by pressing the plunger against a smooth surface of concrete which has to be firmly supported. The equipment used for this method are:

1- Schmidt hammer.
2- Abrasive “grinding” stone.
3- Calibration anvil.

The Schmidt hammer procedures are:

1. Place the Schmidt Hammer perpendicularly to the surface of the tested concrete.
2. Press housing against the test surface at moderate speed until it impacts.
3. Estimate the rebound number on the scale.
4. Record 10 readings.
5. Find the average rebound number.
6. Find the estimated compressive strength from the conversion curve.

B. Split Tensile Strength Test

This test consists of applying a compressive force along the length of a cylindrical concrete specimen at a prescribed rate range until failure occurs; this loading includes tensile stresses on the plane containing the applied load and relatively high compressive stresses in the area immediately around the applied load.

The procedure of the test is as follows:

- Measure the diameter of the cylinder two to three times using a digital Vernier, and take the average.
- Measure the length of the cylinder twice to compute the average height of the cylinder.
- Take the weight of the cylinder specimen using an electronic balance.
- Calculate the density by dividing the weight by volume
- Record the maximum applied load.

C. Flexural Strength Test

This test is used to determine the modulus of rupture of concrete specimens by the use of a simple beam with center-point loading.

- Measure the width and the depth of the beam twice using

Vernier caliper to calculate the average dimensions.

- Use the compression machine to apply load on the beam and note down the maximum applied load

VIII. Conclusions

The properties of the 3D concrete printing both in the fresh and hardened states are reviewed in this paper. The mixes of the 3D concrete printing and materials used have been evaluated. 3D printing on a large scale is said to be time saving and economical in which the only significant cost is the 3D printing robot which is a one-time initial cost. 3D printed concrete; additionally, minimizes the pollution of environment and decreases injuries and fatalities on construction sites. The main challenges facing this technology and preventing it from being on display are having a concrete mix that can maintain its shape when it is extruded from the nozzle, carry the load of multi layers without changing their dimensions. These problems can be addressed by trying different trial mixes with different materials and different percentage of each ingredient. The additives we used are polyethylene fibers, nano silica and the use of admixtures that are accelerator, VMA and superplasticizer. This study reviewed the history behind 3D concrete printing, its advantages and the obstacles that are facing the wide spread of this technology.

There is need to assess the structural stability of the 3D concrete by testing the bond between interlayers of the concrete.

References

[1] "Berok Khoshnevis wants to 3D print houses with Contour Crafting on earth and on the moon," *3ders.org*. (Online). Available: http://www.3ders.org/articles/20160802-berok-khoshnevis-wants-to-3d-print-houses-with-contour-crafting-on-earth-and-on-the-moon.html. (Accessed: 19-Sep-2017).

[2] NASA's Centennial Challenges: 3D-Printed Habitat Challenge," *NASA*, 05-Oct-2016. (Online)

[3] J. E. N. Kinney, "Spanish City Installs 3D-Printed Bridge," *Next City*, 15-Dec-2016. (Online)

[4] R. Rael and V. S. Fratello, "Developing Concrete Polymer Building Components for 3D Printing," pp.152-157, 2011

[5] N. G. Society, "Non-Renewable Energy Resources," National Geographic Society, 23-Sep-2015. (Online). Available: https://www.nationalgeographic.org/activity/non-renewable-energy-resources/. (Accessed: 09-Nov-2017).

[6] I. Hager*, A. Golonka, and R. Putanowicz, "3D Printing of Buildings and Building Components as the Future of Sustainable Construction?" *Science Direct*, 03-Aug-2016. (Online). Available: http://www.sciencedirect.com/science/article/pii/S1877705816317453. (Accessed: 18-Sep-2017).

[7] Malaeb, Zeina & Hachem, Hussein & Tourbah, Adel & Maalouf, Toufic & El Zarwi, Nader & Hamzeh, Farook. (2015). 3D Concrete Printing: Machine and Mix Design. International Journal of Civil Engineering and Technology. 6. 14-22.

[8] S. Sanju, S. Sharadha, and J. Revathy, "Performance on the Study of Nano Materials for the Development of Sustainable Concrete," International Journal of Earth Sciences and Engineering, vol. 9, no. 3, pp. 294–300, Jun. 2016.

[9] ASTM C1437 – 15, Standard Test Method for Flow of Hydraulic Cement Mortar, ASTM International, West Conshohocken, PA, 2015.