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Printable Hollow Concrete Beams by 3D Concrete Printer

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Abstract
3D printers are constantly developing and have a wide range of uses. Today, it is actively used in many fields, from the production of implants and prostheses to the production of jewelry. This technology, which is widely used in civil engineering in areas such as building element production, sustainability, and building construction offers several advantages over conventional concrete pouring and processing methods. Decreasing material waste, decreasing labor costs, freedom and originality in design, and saving time are among these advantages. In this context, 3DCP compared to traditional methods, it reduces the use of materials and makes the construction process more efficient since it is designed with different internal patterns and hollows. This study focuses on the printing process of hollow concrete beam designs in 3 different patterns with 2 different mixtures. Crushing between the layers of beams printed with 3D concrete printing, layer height, and printability and fresh state tests of the mixtures were examined.

1. Introduction

In a rapidly changing world, technology also advances and develops at the same pace. With these developments, new automation process that will make people's lives easier are also emerging. 3D printers, which are a type of additive manufacturing, operate successfully in the construction industry as well as many areas. This technology, which reduces material waste and labor cost, has shown the same benefits in the construction industry as in other sectors, with the gain in production time [1].

Each stage in the traditional application of concrete, one of the most used materials in the construction industry, requires high costs, labor and time. High dependence on labor can lead to loss of time, poor quality production, and material waste. Another problem with traditional methods is the limitation of design freedom. Since the use of formworks in reinforced concrete structures is not used in 3D Concrete Printing (3DCP) technology, designs with complex geometries can be produced easily, It has become clear that there is a problem in this regard, as it constitutes approximately 80% of those involved in the waste generated in the construction industry [2]. This is one of the reasons for increase in waste in the construction industry, as formworks are eventually thrown away.

On the other hand, working in construction sites and manufacturing areas has conditions that pose risks to employee health. The fact that construction sites are messy, large and generally outdoors poses many risks in the sector. Due to these conditions, the working area is exposed to many effects and dangers and is also highly affected by weather conditions [3].

Considering what 3DCP technology offers; Advantages such as reducing the cost because no formwork is used, saving time by working continuously at a constant level, contributing to sustainability by reducing construction waste, adding freedom and originality to the design, contributing to the protection of workers' health by reducing risky work, may play an important role in solving the mentioned problems [4]. In the literature, studies on

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recycling to reduce cost or CO_2 emissions [5]-[19], it is thought that it is important for both engineering and sustainable production to evaluate the mechanical and durability properties of concrete or mortar content together in pavement design in future studies such as these.

The first 3D concrete printing technique, which Khoshnevis calls Contour Crafting (CC), is an additive manufacturing method with significant potential in the automatic production of small-scale structures [20]. Contour Crafting has been an important development in the transition to automation for the construction industry, which lags behind in automation compared to other sectors.

The Concrete Printing method promises to reduce construction costs due to the possibility of not using formworks. This technology, which enables production in complex geometries, cannot produce a smooth surface compared to Contour Crafting. This method, which requires a manual process for a smooth surface, is against automation and has a disadvantages compared to Contour Crafting [21].

In the additive manufacturing technique called D-Shape, unlike other methods, production is made with powder and adhesive layers instead of a paste-like cement-like material. Following a programmed route, the nozzle sprays a liquid that adheres to the bed. The extruded material reacts and begins solidify, and in the continuation of the process, this movement is repeated, and accumulation is ensured.

Studies on 3DCP technology are continued by different teams in many points of the world. The 3DCP facility established by a group of researchers at Eindhoven University makes a mixture of traditional components used in concrete and printing in layers. The printer's head is independent of its axis, while the X, Y, Z axes also make movement possible. While all the parameters required for the movement are under control, designs in the originality and freedom emerge [22].

Significant studies have been carried out and contributed to literature about design freedom and optimized printable elements, which are major promises of this technology. In the study conducted by Gosselin et al., a "multifunctional wall" consisting of 139 layers was designed. Fiber reinforced Ultra High-Performance Concrete (UHPC) is used in this building element. The production of the element with a dimensions of 1360 mm x 1500 mm x 170 mm lasted approximately 12 hours [23].

In Asprone et al. [24] study, designed a prefabricated beam in different geometry. Due to the low tensile strength of concrete this prefabricated beam is strengthened by steel reinforcement from the outer surface. Designed for long spans, such elements must pass different tests with loading.

Wang et al. [25] designed five different concrete mixtures using ceramcite sand and silica sand. The optimized mixture was selected to work in harmony with the printing process. Four different types of hollow cubic and beam elements were printed with selected mixture. The internal pattern of the elements was planned as lattice, cellular, triangle and, truss. As a result of the tests, the rectangular lattice hollow cubic sample has the best mechanical resistance against compression, and the truss-shaped prism structure shows the best flexural strength.

In one of the studies that contribute to the literature about the structural elements in different geometries, Dey et al. [26] printed the beams in 3D, while they examined the beams through the computer with Finite Elements (FE) method. They reported that the best resistance against bending deformation belongs to the triangular pattern in this study, which they think will benefit in designing large scale structures.

2. Material and Method

Concrete required to work compatible with a 3D printer must meet certain requirements. It distinguishes this concrete from conventional concrete in that it can withstand its own weight because it is printed layer by layer, has a flowable consistency for exiting the nozzle, and the workability of the concrete in the printer maintains while the printing process continues. There is no standard yet for mixtures to be used in 3D printing. However significant studies in the literature have made some determinations for printable mixtures as a result of their traditional tests.

2.1. Extrudability

In a mixture where extrusion is successfully achieved, it is expected that the nozzle maintains its shape after the concrete leaves the nozzle, it does not block the nozzle at all, the flow is not interrupted during exit, and the process proceeds repeatedly [27]. In this study, fine aggregate was used to avoid blockage since the nozzle diameter was 15 mm. The fine sand used also helped create the required spreading. Low flowability was avoided because extrudability was stated to be related to flowability [28]. Visual observations were used to determine whether extrusion was achieved.

2.2. Workability

The Slump Test (a) Figure 1. which is a simple and useful test for the workability of concrete, is widely used to determine consistency. In this experiment that correlates with shear strength, Özalp et al. it states that mixtures with 200 mm slump value can be printed in only 3 layers, but mixtures with 190 mm slump value can be printed easily [29]. As a result of the Slump Test ASTM C143 [30] conducted in this study, it was observed that 2 mixtures obtained with slump values of Mix-2 185 mm and Mix-1 190 mm could be printed. In order to add workability to the mixture, methods are being tried to reduce the shear strength by increasing the water/cement ratio of the mixture and adding superplasticizer to the mixture, and if there is amount of superplasticizer, increasing it percentage compared to the cement [29]. Another test evaluated to get an idea about workability is the ASTM C1437-20 [31] Flow Table Test (b) and (c) Figure 1. Tay et al. [32] defined the printable region as a diameter value of 15-19 cm. they stated that mixtures with this diameter value are workable and also allow for higher buildability. Mixtures with a diameter below 15 cm almost block the nozzle and have difficulty in being extruded (a) Figure 2. It was observed that the layers of the mixtures with diameter above 19 cm spread after extrusion and the layers interpenetrate with each other, and the mixture could not be printed successfully (b) Figure 2. Successful extrusion in (c) Figure 2. Mix-1 has a diameter value of Flow Table 16,6 cm and Mix-2 has a diameter value of Flow Table 16 cm.

2.3. Buildability

Layers printed on top of each other support each other's weight and maintain their shape, indicating buildability. Some studies determined buildability as the maximum number of layers that could be printed without important deformation [33], while other studies determined it by measuring the vertical settlement of printed layers [34]. According to Austin [35] buildability in 3D printable concrete is defined as the number of layers without significant deformation of the lower layers. In this study, the total layer height of the beams printed in 10 layers was measured as 110 mm in the measurement made immediately after printing, and when the total layer height of the hardened state was measured, it was found that this value decreased between 105-108 mm.

Figure 1. Slump Test (a) and Flow Table Test (b), (c)

Figure 2. a) Flow Table Diameter Value Below 15 cm
b) Flow Table Diameter Value Above 19 cm
c) Flow Table Diameter Value Between 15-19 cm

2.4. Process of Printing Concrete

In this study, studies in the literature were examined and based on the reference mix designs, sand, cement, silica fume, fly ash, superplasticizer, and water were used to produce printable concrete as a result of preliminary trials. Two mix designs were created by using these materials in different proportions. Coarse aggregates were not preferred to avoid blockage of the 15 mm nozzle diameter, which is the exit point of the printer. In order not to increase the w/b ratio too much while maintaining workability, the amount of superplasticizer was increased in a mixture and fly ash was used in the mix due to its ability to reduce the need for water. The cement type used in the mixtures is CEM-I 42.5R. MasterGlenium51, which increases the workability time was chosen as the superplasticizer. Before adding water and superplasticizer to the mixture, the dry materials were mixed in a drum type mixer for 2 minutes. Then 50% of the mixture water was added and the mixture was mix for 1 minute. Superplasticizer was added to the remaining mixing water as recommended [36] and the mixer was stopped. After the mixer was scraped with a trowel, the remaining mixing water and superplasticizer were added while the mixing process continued. Finally, the mixture was mixed for 1 more minute and then the resulting concrete was taken from the mixer. Beams with 10 layers and dimensions of 600 mm x 200 mm x 110 mm were produced. Three different internal patterns were selected to be printed with a 3D printer. These internal patterns are called wave shape (a), rectangular shape (b), parallelogram shape (c) in Figure 3. The volume occupancy rates of the internal patterns of these shapes are wave shape has 25%, rectangular shape has 28%, parallelogram shape has 50%. Elements that failed in preliminary attempts during the printing process are shown in Figure 4. The mix designs created are included in Table 1 and Table 2.

Table 1. Mix Design-1 (kg/m^3), w/b ratio: 0,40

Material	Amount
Sand	1220
Cement	630
Silica Fume	74,8
Fly Ash	19,7
Superplasticizer	3,95
Water	291

Table 2. Mix Design-2 (kg/m^3), w/b ratio: 0,37

Material	Amount
Sand	1200
Cement	640
Silica Fume	76
Fly Ash	24
Superplasticizer	5
Water	280

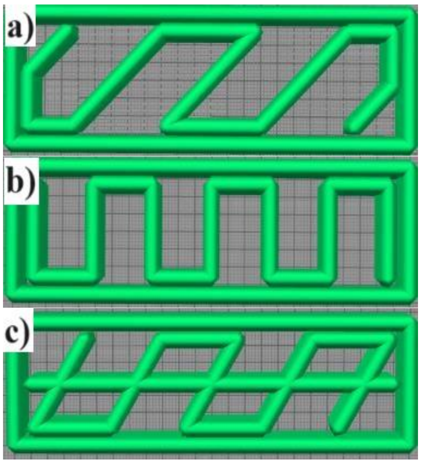

Figure 3. Different internal patterns
a)Wave shape
b)Rectangular shape
c)Parallelogram shape

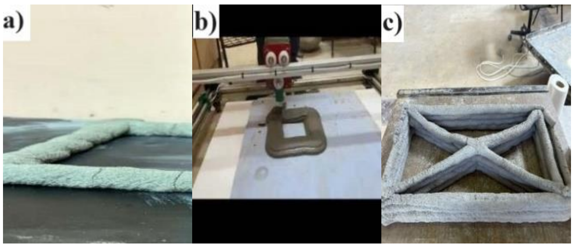

Figure 4. a) Shrinkage crack
b) High flowability because of high amount of superplasticizer
c) Thin layers because of low w/b ratio

3. Results

Mix designs that work compatible with the printer after extrusion process have yielded successful results. A total of 6 samples in 3 different patterns with 2 different mix designs were successfully produced with a 3D concrete printer. Hollow concrete beams with internal patters of wave shape, rectangular shape, and parallelogram shape have reached a height of 110 mm in 10 layers. From the beginning to the end of the printing process, there were no problems such as blockage in the nozzle, deformation of the hollow concrete beams, or interpenetration of layers. Situation such as loss of function, loss of flowability, segregation, and heterogeneity were not observed in either of the two mix designs created to work compatible with the 3D printer. Immediately after the printing process, the crushing between the layers of the hollow concrete beams was examined and the total height was measured. This measurement was made again after the hollow concrete beams had dried. In the dry state measurement made on the hollow concrete beams print with Mix Design-1, it was observed that the height of the parallelogram shape among all the hollow concrete beams, which was initially 110 m, decreased to 105 mm, and the rectangular shape and wave shape decreased to 106 mm. In the dry state measurement made on the hollow concrete beams print with Mix Design-2, it was observed that the height of the parallelogram shape among all the hollow beams, which was initially 110 mm, decreased to 107 mm, and the height of the rectangular shape and wave shape decreased to 108 mm. During these height decreases, the layers were examined one by one, and it was determined that there was no significant visible deformation in any layer.

Figure 5. 3D Printed Hollow Concrete Beams

Figure 6. Fresh State Height Measurement

Figure 7. Hardened State Height Measurement

4. Conclusion

Considering the investigations, experiments and observations made in this study, it is possible to make some inferences about the effect of mix designs, w/b ratio, concrete printing process, and volumetric filling ratio of internal patterns. During the printing process, printing begins by assuming that the layers will be at the same height, but looking at the results, as the layers accumulate on top, there may be a slight loss in the layers below due to weight.

- When the volumetric filling ratio is examined, it is seen that the parallelogram shape, whose internal pattern is 50% filled, is the shape that suffers the most height loss for both mix designs. A 4.5% height loss in Mix-1 of the parallelogram shape; It was observed that there was a 2.7% height loss in Mix-2. It is thought that the reason why this shape experiences different levels of loss in the 2 mixes is that Mix-1 has a higher w/b ratio and contains more water. When the rectangular shape with a volumetric filling rate of 28% and the wave shape with a volumetric filling rate of 25% are examined, the measured height loss for Mix-1 is 3.6%; It was observed that the measured height loss for Mix-2 was 1.81%.
- When approaching the study in terms of extrudability, as stated and shown in the photographs, it is pointed out that there are no issues with extrusion. Mix-1 and Mix-2 do not cause blockage in the nozzle for a 3D concrete printer under laboratory conditions, the nozzle shape is maintained after the concrete exit, and the flows are not interrupted.
- When the issue of workability is considered, Mix-1 and Mix-2 have a Flow Table diameter of 15-19 cm, which is called the printable region in the literature, and Slump Test values are 190 mm and 185 mm. The fact that Mix-1 and Mix-2 are easily printed in a flowable manner without losing their homogeneity indicates that there is no issue in terms of workability about these 2 mixes.
- Visible deformation of the layers, which is an important visual data in buildability, was not experienced in the samples presented in this study. It was determined that there was a maximum loss of 4.5% in samples with final height values in the range of 105-108 mm. This paper focuses on the printability of 3 hollow concrete beams with different internal pattern with 2 different mix and was conducted with the aim of expanding experimental studies in the future to print elements of complex geometry with different mix designs in a laboratory environment with a laboratory-scale 3D concrete printer.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

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