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M.Sc. in Civil Engineering

FURKAN BORAN AKKOYUN

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EXPERIMENTAL INVESTIGATION OF HOLLOW CONCRETE BEAM WITH SEVERAL CONFIGURATIONS PREPARED BY USING 3D PRINTER TECHNOLOGY

M.Sc. THESIS

IN

CIVIL ENGINEERING

BY

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Supervisor

Prof. Dr. Nildem TAYŞİ

Co-Supervisor

Asst. Prof. Dr. Osman HANSU

by

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submitted by **Furkan Boran AKKOYUN** in partial fulfillment of the requirements for the degree of Master of Science in **Civil Engineering, Gaziantep University** is approved by,

Prof. Dr. Çiğdem AYKAÇ
Director of the Graduate School of Natural and Applied Sciences …………............

Prof. Dr. Nildem TAYŞİ
Head of the Department of Civil Engineering …………............

Prof. Dr. Nildem TAYŞİ
Supervisor, Civil Engineering
Gaziantep University …………............

Asst. Prof. Dr. Osman HANSU
Co-Supervisor, Civil Engineering
Gaziantep Islam Science and Technology University …………............

Exam Date: 11 June 2024

Examining Committee Members:

Prof. Dr. Nildem TAYŞİ
Gaziantep University …………............

Prof. Dr. Amjad KHABAZ
Hasan Kalyoncu University …………............

Assoc. Prof. Dr. Mehmet Tolga GÖĞÜŞ
Gaziantep University …………............

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Furkan Boran AKKOYUN

ABSTRACT

EXPERIMENTAL INVESTIGATION OF HOLLOW CONCRETE BEAM WITH SEVERAL CONFIGURATIONS PREPARED BY USING 3D PRINTER TECHNOLOGY

AKKOYUN, Furkan Boran
M.Sc. in Civil Engineering
Supervisor: Prof. Dr. Nildem TAYŞİ
Co-Supervisor: Asst. Prof. Dr. Osman HANSU
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Three-dimensional printers, which are constantly developing and have a wide range of applications, are actively used in many fields today, from spare part production for automobiles to the manufacturing of prosthesis and implants, as well as from food production to sculpture and jewelry production. In civil engineering and architecture, the use of this technology has become widespread in areas such as modeling, manufacturing of structural elements, construction, restoration, and sustainability, offering various advantages over conventional concrete casting and processing methods. Among these advantages are reducing material waste, lowering labor costs, free and unique design, and time savings. In this context, hollow beams to be manufactured with 3D Concrete Printer technology will further enhance the potential advantages in the construction industry. In this study, two different printable concrete mixtures were prepared and hollow beams in three different patterns were designed. The flexural strengths of the designed hollow beams were determined and the extrudability, workability, buildability, open time, and compressive and flexural strength values of two different printable mixtures were examined.

Key Words: Hollow Concrete Beam, Printable Concrete, 3D Printer Technology

ÖZET

3D YAZICI TEKNOLOJİSİ KULLANILARAK FARKLI TASARIMLARDAKİ BOŞLUKLU BETON KİRİŞ NUMUNELERİNİN DENEYSEL OLARAK İNCELENMESİ

AKKOYUN, Furkan Boran
Yüksek Lisans Tezi, İnşaat Mühendisliği
Danışman: Prof. Dr. Nildem TAYŞİ
İkinci Danışman: Dr. Öğretim Üyesi Osman HANSU
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51 sayfa

Sürekli gelişen ve geniş bir uygulama alanına sahip olan üç boyutlu yazıcılar, günümüzde otomobil yedek parça üretiminden protez ve implant imalatına, gıda üretiminden heykel ve takı üretimine kadar pek çok alanda aktif olarak kullanılmaktadır. İnşaat mühendisliği ve mimarlıkta modelleme, yapı elemanlarının imalatı, inşaat, restorasyon ve sürdürülebilirlik gibi alanlarda kullanımı yaygınlaşan bu teknolojinin, geleneksel beton döküm ve işleme yöntemlerine göre çeşitli avantajları bulunmaktadır. Bu avantajlar arasında malzeme israfının azaltılması, işçilik maliyetlerinin düşürülmesi, ücretsiz ve benzersiz tasarım ve zaman tasarrufu sayılabilir. Bu kapsamda 3D Beton Yazıcı teknolojisiyle üretilecek boşluklu kirişler inşaat sektöründeki potansiyel avantajları daha da artıracak. Bu çalışmada iki farklı yazdırılabilir beton karışımı hazırlanmış ve üç farklı desende içi boş kirişler tasarlanmıştır. Tasarlanan içi boş kirişlerin eğilme dayanımları belirlenmiş ve iki farklı yazdırılabilir karışımın ekstrüde edilebilirlik, işlenebilirlik, inşa edilebilirlik, açık zaman ve basınç ve eğilme dayanımı değerleri incelenmiştir.

Anahtar Kelimeler: Boşluklu Beton Kiriş, Yazdırılabilir Beton, 3D Yazıcı Teknolojisi

''Dedicated to my family''

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LIST OFABBREVIATIONS

3D	Three-Dimensional
3DCP	3D Concrete Printer
3DPC	3D Printed Concrete
Acc	Accelerator
AMoC	Additive Manufacturing of Concrete
ASTM	American Society for Testing and Materials
C	Cement
CC	Contour Crafting
cm	Centimeter
cm^3	Cubic Centimeter
FE	Finite Elements Simulation
FS	Fine Sand
g	Gram
kg	Kilogram
lt	Liter
M1	Mix Design-1
M2	Mix Design-2
m^3	Cubic Meter
mm	Milimeter
Mpa	Megapascal
Noz	Nozzle
pH	Power of Hydrogen
R	Retarder
R&D	Research and Development
Sec	Second
SP	Superplasticizer
TS EN	Turkish Standards European Norm
UHPC	Ultra-High-Performance Concrete

W	Water
W/B	Water to Binder Ratio
W/C	Water to Cement Ratio
WR	Water Reducer Additive
X	X Axes
Y	Y Axes
Z	Z Axes

CHAPTER 1
INTRODUCTION

1.1 General

As the world changes day by day, technology develops at the same pace and offers innovations that make life of society easier. With the effect of development, change and consumption, the use of resources, raw materials and materials is increasing, and the existing facilities are faced with being insufficient for these uses. One of the important expectations of humanity from developing technology is to meet the needs in a shorter time with the use of less material, while not exceeding the cost limit. At the intersection of these expectations and needs, the entry of three-dimensional (3D) printer technology and its successful works in different sectors are promising for the future. With the advancement of 3D printer technology, this innovation has also entered the construction industry. 3D printing devices have demonstrated the same benefits in the construction industry as they do in other industries, with their fast production times [1].

In the traditional application of concrete, which is one of the most used materials in the construction industry, each of the production, transportation, pouring, and processing stages requires significant workmanship, cost, and time. Since the dependence on workmanship is high in traditional methods; material waste, loss of time and lack of quality are among the problems that may be experienced in the construction industry. In reinforced concrete structures, formwork, that support the steel and concrete to hold together and support the process of reaching sufficient strength of the structural element, restrict the design freedom and originality in the structure. Since 3D Concrete Printer (3DCP) technology does not require a formwork, it allows designs with complex geometry to be freely manufactured.

Considered from another perspective, the serious amount of waste produced in the construction industry means another difficulty. Formworks are an important source of waste production because they are all discarded eventually and are one of the reasons for the increasing amount of waste production in the construction industry. The spectacular detail presented in Llatas' research indicated that the construction industry is liable for nearly 80% of the world's entire waste [2].

Moreover, working in construction sites and manufacturing areas in the construction industry has various difficulties and working conditions that endanger labors health. The main reason for the high rate of occupational accidents in the construction industry is that the construction industry has specific working conditions. The main reason why the construction industry is different from other sectors is that each project is different from each other, and the construction site is large, dispersed and has various working conditions, which causes various risks. It carries many risks due to working mostly outdoors. The work area is generally open to all kinds of influences and dangers that may come from outside and is highly affected by weather conditions [3].

Considering sustainability as another issue in the construction industry, it is an important problem today. Generally, conventional construction methods and materials are not eco-friendly. The whole construction process, which includes manufacturing, transportation, installation and assembly, and on-site construction time , spreads large amounts of greenhouse gases and consumes large amounts of energy [4].

It may be possible to solve the mentioned problems with the developments made in 3DCP technology. The mentioned problems continue to be encountered in traditionally produced structures and concrete. Compared to traditional methods, 3DCP technology may offer significant advantages including:

1. Decreasing construction costs by not using formwork;

2. Reducing physical injury rates by removing risky jobs which would result in an increased safety level in construction;

3. Creation of high-tech jobs;

4. Reducing construction time on site by working at a constant level;

5. Reducing the possibility of mistakes by considerably precise material deposition;

6. Increasing sustainability in construction by reduction of wastages of formwork,

7. Increasing architectural freedom, which would allow more sophistical designs for structural and aesthetic aims; and

8. Activating potential of multifunctionality for architectural/structural members by taking advantage of the complex geometry [5].

1.2 Aim of the Study

This study focuses on concrete mix designs that can be printed with 3DCP's and on examining the flexural strength of hollow concrete beams in several configurations produced through 3DCP's. In the study, while determining the flexural strength values of hollow concrete beams in different patterns, the extrudability, workability, buildability, open time, and compressive and flexural strength values of the mix designs used were also examined. In this study, which aims to contribute to the 3DCP technology literature by both preparing mixtures and printing elements with complex geometry, the highest flexural loads that hollow concrete beams with different patterns withstand will be determined. During the work, mixtures that can work compatible with the machine are designed by using materials such as fly ash, silica fume, superplasticizer and adjusting the water/cement ratio. Since the structural elements of complex geometry, which is the focus of the study, will be printed without formwork using 3DCP technology, it also aims to give an idea about the important points that this technology, which is expected to become widespread in the future, can reach. Since without formwork production reduces environmental waste, time loss and costs, it is an important parameter for it to become more widespread in the future as it is a high-yield technology. In addition, the ability to work freely within complex geometry emerges as another reason for it to become widespread in the future, as it brings freedom and originality in design. During the study, the laboratory of Gaziantep University Civil Engineering Department was used and the 3DCP within the Gaziantep University Civil Engineering Department was used.

1.3 Chapter of the Thesis

Chapter 1- Introduction: General information about the usage areas, advantages, and place of 3D printers in the construction industry is given. The importance of elements in complex geometry has been introduced.

Chapter 2- Literature Survey: Studies on 3DCP's, printable concrete mix designs, and elements with complex geometry such as hollow concrete beams are mentioned.

Chapter 3- Materials and Methods: Information is given about the methods and materials used during the work.

Chapter 4- Experimental Studies: Prepared concrete mixtures, designed and produced hollow concrete beam samples and experiments are presented.

Chapter 5- Results and Discussions: Findings, experiments on concrete mixture and hollow concrete beams are presented and the results are mentioned.

Chapter 6- Conclusions: The conclusion of the thesis is included.

CHAPTER 2
LITERATURE SURVEY

Contour Crafting (CC), the first known 3D concrete printing technique, is a layered production technology with significant potential in the automatic production of small structures. It is alleged by Khoshnevis that an entire structure can be built using this process, even if each design is different. Automation, which has advanced in different industrial sectors, could not show the necessary development in the construction sector. Automation methods used in construction are not sufficient for the construction of large-scale structures. CC has significant potential in terms of automation for the construction industry [6].

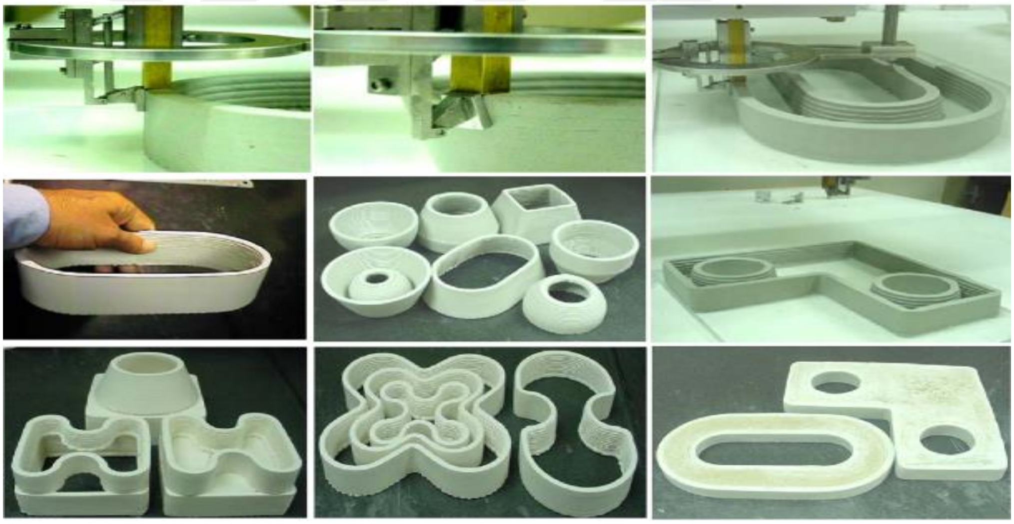


Figure 2.1 CC Technology.

Not using formwork during the building construction process is an important factor that reduces costs. The Concrete Printing method offers the opportunity to not use formworks. In this technique, which does not use a trowel, unlike contour work, a finer residue dissolvability is needed to achieve high three-dimensional flexibility. However, while this situation allows complex geometries to be controlled and obtained, it increases costs [7].

Concrete Printing may have a disadvantage compared to CC. If a smooth surface is expected after the process, manual troweling or grinding of a smooth surface is required. Since it is done manually, it is against automation and is a disadvantage compared to contour crafting [7].

Figure 2.2 Concrete Printing method.

In the method called D-Shape by Enrico Dini, unlike the previous mentioned methods, powder and adhesive layers are used, not a cement-like paste. Following a programmed trajectory, the nozzle head extrudes an adhesive fluid into the sand-bed. The extruded material begins to solidify under the influence of the reaction. In the ongoing process, a new layer is added, and the process is repeated, ensuring deposition on the surface. The D-Shape method demonstrated its capabilities by 3D printing the Radiolaria Pavilion with complex geometry in 2008 and the Ferreri house in 2010 [5].

Figure 2.3 D-Shape method, Enrico Dini.

CC, Concrete Printing and D-Shape techniques, which have different aspects and advantages, are also used for different applications and different materials. For this reason, unlike there being a competition between them, they provide different opportunities for different designs [7].

Many teams at many points around the world are working on 3DCP technology. One of these teams, the 3DCP Facility at the University of Eindhoven, creates the desired design by extruding the mixture created using water, cement, aggregate and sand, which are conventional materials for concrete mixture, through the nozzle to print the layers. While the head of the 3DCP can rotate around itself, there is also freedom of movement in the x, y, z axes. Thus, while freedom in design is no longer a problem, parameters such as speed, angle and acceleration are taken under control [8].

Figure 2.4 3DCP Facility at University of Eindhoven.

In the 2010s, with the use of 3D printers in concrete and the start of building production studies with these printers, examples that various individuals and companies designed and produced on a building scale emerged.

Chinese company WinSun, which wants to work on how 3D technology can also produce high-rise buildings, prints 3D structures with its own 3DCP. Winsun company prefers to print the building elements, transport them to the site and assemble them on site, rather than printing the entire structure on site. WinSun has developed many residential projects, including the construction of a miniature apartment building [9].

Figure 2.5 WinSun company printed 5-storeys building.

Dubai Municipality Office in the United Arab Emirates has an important place among large-scale 3D printed structures. This building, which was completed by the Apis Cor company in late 2019, spreads over an area of 640 square meters and has a height of 9.5 meters [10].

Figure 2.6 Dubai Municipality Office printed by Apis Cor.

Born from the combination of technology and clay words, TECLA was launched in 2021 with the three-dimensional printer developed by Crane WASP for the construction industry in Massa Lombarda (Ravenna / Italy). The structure produced using natural earthenware represents an important step in this field with the opportunities provided by three-dimensional printing technology [10].

Figure 2.7 Works of TECLA Company.

At Loughborough University in England, Dr. The research team, led by Richard Buswell, has been developing a proprietary 3DCP technology for the production of full-scale construction and architectural parts since 2014. This technology creates architectural features in concrete elements and produces low-cost complex facade panels using construction waste [11].

In September 2017, BAM Infrastructure group, in collaboration with Eindhoven University of Technology, completed and assembled a 3D printed bicycle bridge in Netherlands. The project began in June 2017 with the planning and design of the printing process. The bridge, 8 meters long and 3.5 meters wide, is a unique example in the Netherlands. Bridge elements were printed separately and then combined with prestressed and reinforced concrete. Bicyclists use this bridge to cross a channelized river called the Peelsche Loop [12].

Figure 2.8 3D printed bicycle bridge in Netherlands [12].

Research-development studies, scientists, and articles resulting from academic laboratory studies have made significant contributions to these important companies and individuals in bringing 3D concrete printing technology to this level.

Le *et al.* [13] discusses experimental results on the mix design and fresh properties of high-performance fiber-reinforced fine aggregate concrete for printing concrete. This concrete is designed to be printed with a 3DCP, suitable for additive manufacturing. This printing process, which enables the production of architectural and structural elements without the need for a formwork, differs from the traditional concrete casting and processing process in that it does not require a formwork. It presents that the parameters related to workability, and open time are directly related to the mixing ratios and the presence of superplasticizer, retarder, accelerator, and polypropylene fibers.

Bos *et al.* [8] the additive manufacturing technique is becoming increasingly common in the construction industry. Additive Manufacturing of Concrete (AMoC), which is one of the methods tried to be applied both in academic studies and in the construction-site, is still in its early stages, despite the researchers and organizations operating in this field. Subjects such as design, materials, and processes, on which research focuses, are being developed and improved day by day. In this study focusing on additive manufacturing methods of concrete, the 3DCP facility at Eindhoven University of Technology is presented in detail. This study, which also investigates the current place and future potential of this technology, discusses all the details of 3DCP technology.

Shakor *et al.* [14] focuses on 3D printing of different concrete mixtures with a 6-degree-of-freedom industrial robot. This study examines the performances of different concrete mixtures used as filaments in the 3D printing process and enables the comparison of the results. Many experiments were carried out to determine the buildability, flowability, extrudability and moldability of concrete mixtures. Horizontal experiments were performed to determine flowability and consistency, and vertical and squeeze-flow experiments were performed to determine the buildability of the layers.

Table 2.1 Shakor *et. al* [14] Mix Designs (C: cement, FS: fine sand, W: water, R: retarder, Acc: accelerator, SP: superplasticizer, WR: water reducer, Noz: nozzles).

Trial No	C (gr)	FS (gr)	W (ml)	R (ml)	Acc (ml)	SP (ml)	WR (ml)	Noz (mm)
1	1000	0	360	8	4	10.4	-	⌀20
2	1000	500	300	8	4	10.4	-	⌀20
3	500	500	150	4	4	5.2	-	⌀20
4	750	750	292.5	4	4	5.5	-	⌀20
5	750	750	250	4	5	5	-	⌀20
6	1500	1500	550	8	10	11	-	20x20
7	1000	1000	361.6	5.33	6.6	6.67	-	20x20
8	1000	1000	343	5.33	6.6	6.67	-	20x20
9	1000	1000	350	5.33	6.6	6.5	-	20x20
10	1000	1250	375	5	6	5	3	⌀10

Lediga and Kruger focused on optimizing the concrete or mortar, which is a very important component for an efficient printing process, and the main parts of the system are the optimized printable concrete mix, the concrete pump, a computerized gantry system, and the extruder. In this study, where the system is controlled a computerized gantry system, an examination of the important points regarding the optimum concrete mixture is presented [15].

Table 2.2 Lediga and Kruger's [15] Mix Design.

Sand/ Binder ratio: 3/2 Maximum 2mm aggregate size 70% Cement 20% Fly Ash 10% Silica Fume
Additionally,
Water/binder ratio: 0,26
Micropolypropylene fibers(length/diameter): 12/0.18
Superplasticizer (binder weight): 1%
Retarder (binder weight): 0.5%

As a result of the compressive strength test applied from 3 different axes to 100 mm cubes taken from the 350 mm x 350 mm x 120 mm sample created with this mixture, the values varied between 75 and 102 MPa.

Kazemian *et al.* [16] focused on issues such as print quality, shape stability and buildability to evaluate concrete mixtures in their study. Four different mixtures were prepared. The water/binder ratio of all mixtures in this study was chosen as 0.43 and the binder dosage was 600 kg/m^3. Type II Portland cement, sand with a maximum aggregate size of 2.36 mm, water and a high amount of water-reducing additive were used in all mixtures.

In 2018, Özalp *et al.* [17] within the scope of their study, they prepared two different mixture designs for concrete printable with 3DCP technology and presented the experimental data of these mixtures. Silica sand with a diameter between 0-1.5 mm was used as aggregate, and CEM I 42.5 R normal Portland cement and White Portland Cement 52.5 were used as binders. Material mixing ratios of the designed concrete;

cement: water: sand: chemical additive = 1: 0.30: 1.5: 0.02. Plasticizer varying between 1.5% and 2% of the cement weight was added separately to the mixtures. In order to prevent shrinkage and cracks that may occur in the concrete, polypropylene microfibers were used in each mixture at a rate of 600 gr/m³. The mixture with a water/cement ratio of 0.30 and a superplasticizer additive of 1% by weight could not be printed. When the water/cement ratio of the mixture containing the same amount of superplasticizer was increased to 0.40, this mixture also failed because the layers could not support themselves. Superplasticizer amount of the mixture with a water/cement ratio of 0.30 It has been observed that by using an increased amount of cement at a rate of 2% by weight, the concrete can be printed and does not collapse under its own weight.

In their research, Zhang *et al.* [18] conducted studies on the buildability, rheological behavior, workability, fresh strength, open time and hydration heat of concrete designed for 3D printing process. To measure buildability, they measured the maximum printable layer height. They observed that there is a relationship between the fresh strength of concrete, its thixotropic properties, yield stress and buildability. They observed that the addition of nanoclay and silica fume positively affected the thixotropy, fresh strength and buildability of concrete. However, they presented in the study that nanoclay gave better results.

A few studies have been conducted and included in the literature on design freedom and optimized printed structural elements, which are among the most important reasons why 3DCP technology is a promising innovation in the construction industry.

Gosselin *et al.* [19] noted significant advantages when introducing large-scale 3DCP using ultra-high-performance concrete (UHPC).

These advantages are briefly:

(1) It enables the 3D production of large-scale elements of complex geometry without the need for support,

(2) Making full use of 3D printer technology by producing layers of different thicknesses with the tangential continuity method for the slicing technique, which

allows the production of more mechanically robust structures when evaluated structurally.

(3) Using a 6-axis robotic arm instead of an overhead crane or gantry frame to ensure complex geometry design and full control

(4) Providing multifunctionality for structural members using designs of complex geometry.

This introduced technology was used to create a "multifunctional wall" consisting of a formwork to be reinforced with fiber-reinforced UHPC on structural parts or an insulating material for thermal insulation. Some parts were left empty within the plan so that the installation tools could be positioned. The production of this element, consisting of 139 layers, measuring 1360 mm × 1500 mm × 170 mm and weighing 450 kg, took nearly 12 hours [19].

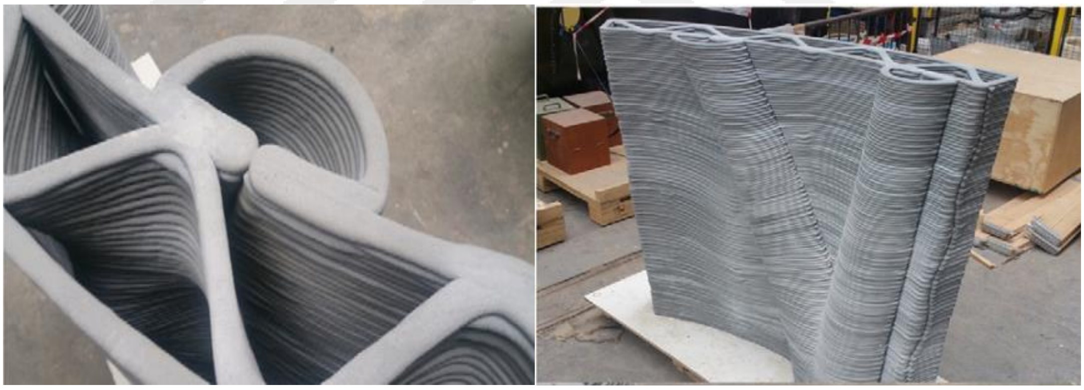


Figure 2.9 Multifunctional Wall printed by Gosselin *et al.* [19].

Elements with different geometries, such as prefabricated beams, have also been designed with 3DCP. This prefabricated beam, which was developed due to the low tensile strength of elements consisting only of concrete, was strengthened with steel reinforcement on the outer surface of the element. This type of elements, which are planned to be used to cross long spans, must pass various tests under loading [20].

Figure 2.10 Work by Asprone *et al.* [20].

Wang *et al.* [21] prepared five different concrete mixtures, including ceramsite sand and silica sand. The optimized mixture has been determined so that it can proceed in harmony with the printing process. Four different types of hollow-structured cubic and beam elements were printed with the selected mixture. The internal pattern of the elements was determined as cellular, truss, triangle, and lattice. As a result of the tests, the rectangular lattice hollow sample showed the best mechanical resistance against compression, while the truss-shaped prism structure was observed to be the beam with the best flexural strength.

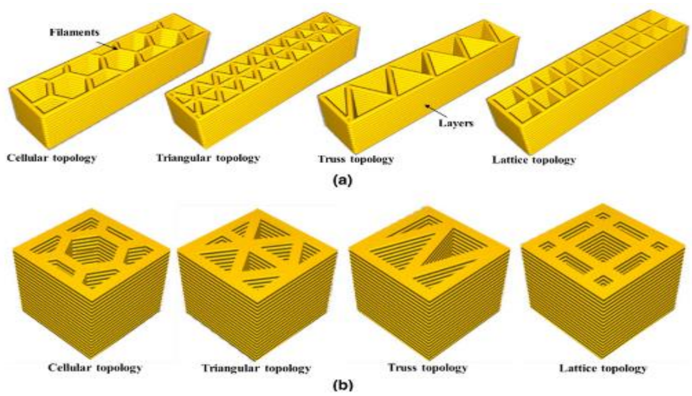


Figure 2.11 Shape of structures with hollow section [21].

Moini *et al.* [22] planned to use interfaces by applying bio-inspired structures in their study and discussed the unique damage mechanisms and fault-tolerant aspects of these structures.

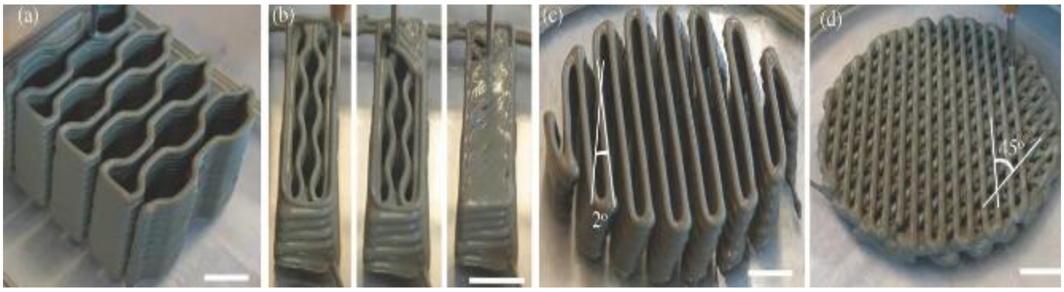


Figure 2.12 Printed materials with different infill pattern by Moini *et al.* [22].

Since there are not many scientific publications on the mechanical performance of structural elements with different internal patterns, Dey *et al.* [23] both 3D printed the beams and examined the beams with Finite Element (FE) simulations in this study. They thought that the results of the study would be useful in different applications of large-scale structures with different complex geometries. As a result of this study, they stated that the strongest resistance to bending deformation belongs to the triangular pattern.

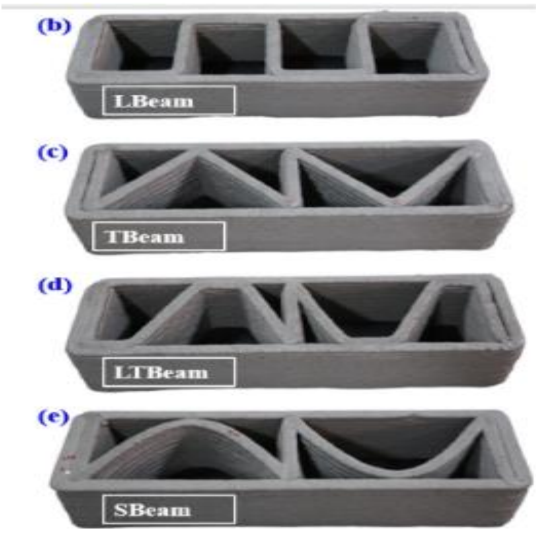


Figure 2.13 Structural elements with internal patterns printed by Dey *et al.* [23].

In their study, Imran *et al.* [24] designed a square-section element with the construction and demolition waste-based mortar they prepared and printed the element with a laboratory-scale 3DCP. In this study, in which they wanted to determine the buildability, the maximum buildability value they could obtain for the element with a layer width of 45 mm was 410.6 mm.

Figure 2.14 A square section element printed by Imran *et al.* [24].

CHAPTER 3
MATERIALS AND METHODS

3.1 Materials

3.1.1 Cement

In this study, CEM II 42.5 R type Portland Composite Cement, produced by ÇİMKO and complying with TS EN 197-1 standard, was used. The physical and mechanical analysis table of CEM II 42.5 R Portland Cement used in experimental studies is given in Table [25]. It has high workability and thanks to the fine filling materials it contains, it tightens the micro pores in the concrete, increases its impermeability and balances the heat of hydration. It is especially preferred in concrete pouring in hot weather and mass concrete.

Table 3.1 Physical and mechanical analysis of CEM II 42.5R type Portland Composite Cement produced by ÇİMKO [25].

Physical and Mechanical Analysis (%)	Result of Analysis
Specific Gravity (g/cm^3)	3.10
Specific Surface (cm^2/gr)	4125
Residue on 45µ sieve (%)	5.3
Residue on 90µ sieve (%)	0.3
Initial Setting Time (minute)	200
Final Setting Time (minute)	300
Soundness (mm)	1

3.1.2 Fly Ash

Fly ash, a by-product of thermal power plants, is one of the widely used cement replacement materials. It is an additive material that becomes prominent with its ability to increase workability and ultimate strength in fresh concrete. It is a binding material that contributes to the production of sustainable environmentally friendly products by reducing the use of cement, which has a high carbon footprint. Its chemical components are given in the table below [26].

Table 3.2 Chemical components of Fly Ash [26].

SiO_2	43,6-64,4
Al_2O_3	19,6-30,1
Fe_2O_3	3,8-23,9
CaO	0,7-6,7
MgO	0,9-1,7
Na_2O	0-2,8

3.1.3 Silica Fume

Silica fume is very fine non-crystalline silica produced in electric arc furnaces as a byproduct of the production of silicon or silicon-containing alloys. Silica fume has a physical effect as well as a chemical effect on the reaction of cement with water. Thanks to its fineness and mineral structure, it accelerates the reaction of cement with water and accelerates the strength of concrete. The fact that the surface area is very high increases the water needs of the place where it is located. The density of the material is 2.2 g/cm^3 and the unit volume weight is 200-250 kg/cm^3 [27].

3.1.4 Superplasticizer

Used a superplasticizer called Master Glenium 51.

Master Glenium 51 contribution provides the following benefits:

• This chemical is used in the production of self-compacting concrete and self-consolidating concrete, which can be easily placed into densely reinforced concrete elements.

• In precast and prefabricated concrete production,

• It is used in ready-mixed concrete production.

Material properties are given in the table below [28].

Table 3.3 Material properties of Master Glenium 51 [28].

Material Structure	Polycarboxylic Ether Based
Appearance	Brown-Liquid
Specific Weight	1,082-1,142 kg/lt
pH	Between 6-7
Alkaline Content	≤3,00
Chlorine Ion Content	≤0,10
Corrosion Behavior	It cover only the components given in EN 934-1:2008, Annex A.1.

3.1.5 Sand

In experimental studies, 0-2 mm fine aggregate obtained from the sand dunes in Gölbaşı district of Adıyaman province was used. The specific gravity of the aggregate used were found to be 2.56 g/cm^3.

3.1.6 Mixing Water

The mixed water component in the study is of drinking water quality and complies with TS EN 1008. Mains water from Şahinbey district of Gaziantep province was used.

3.2 Methods

3.2.1 Properties of Mix Designs

Since 3DPC must have buildability, workability, and extrudability properties, it is more difficult to design the mixture than traditional concrete. Studies have been carried out on the selection of appropriate materials and optimization of mixture amounts for 3D printable concrete and continue to be done today. A high content of binder is required to ensure shape stability. It is necessary to use fine aggregates to prevent segregation during the extrusion and printing process and to prevent the 15 mm nozzle diameter from blockage. Within the scope of this study, two different mixtures were prepared by taking the mixtures mentioned in the literature as reference. In addition to cement content, fly ash and silica fume were used as binders in the mixtures. Superplasticizer was preferred to keep the water/binder ratio low while achieving workability. Master Glenium 51 was chosen as the superplasticizer. Portland Composite Cement (CEM-II 42.5 R) was chosen as cement.

3.2.2 Testing of Fresh Concrete

Standard acceptance criteria and test methods for measuring open time, workability, extrudability and buildability of fresh concrete or mortar to be used in 3D printing have not yet been determined. In current studies, researchers and studies on this subject suggest various test methods to determine these parameters.

3.2.2.1 Extrudability

In a mixture where the extrudability criterion is met, it is expected that the mixture maintains the shape of the nozzle after exiting, does not cause blockage in the nozzle, does not separate during extrusion, and this process continues continuously [29]. In this study, fine aggregate was preferred because the nozzle diameter was small to pass the extrudability criterion. Since it was stated that extrudability is highly dependent on flowability [30], a concrete mixture with a low flowability level was also avoided. Visual observations during the studies were used to determine whether the mixtures passed the extrudability criterion.

3.2.2.2 Workability

The Slump Test ASTM-C143, which can be easily applied in a laboratory environment and provides data about the workability of concrete, allows the determination of concrete consistency. The diameter of the bottom of the slump cone is 20 cm, the diameter of the upper end is 10 cm and the height is 30 cm. The length of the steel rod used to bottle the concrete is 60 cm and its diameter is 1.6 cm. The prepared fresh concrete is placed with the help of a trowel in approximately one-third of the concrete volume that will fill the cone, that is, in 3 layers. Each layer is skewered 25 times separately with a tamping rod. After the skewering of the top layer is completed, the top of the cone is leveled with a trowel or tamping rod. Immediately after all these procedures, the slump cone is slowly pulled vertically upwards by holding its side handles. The withdrawal process of the cone must be completed at a constant speed and within 5 (±2 sec) seconds. By placing the empty cone next to the completely collapsed concrete pile and placing it horizontally on the tamping rod, the distance between the bottom level of the rod and the average height of the upper face of the collapsed concrete is determined as close as possible. The measured value is expressed as the slump value of concrete. In this experiment related to shear strength, Özalp *et al.* [17] state that the mixture with a slump test value of 190 mm and a water/cement ratio of 0.30 and a superplasticizer/cement ratio of 0.02 can be printed easily, but a mixture with a slump test value of 200 mm, a water/cement ratio of 0.40 and a superplasticizer ratio of 0.01 can only be printed in 3 layers. On the purpose of add workability to the mix, ways are being tried to decrease the shear strength by increasing the water/cement ratio of the mix and adding superplasticizer to the mix, and if there is an amount of superplasticizer, increasing it percentage compared to the cement. Another test evaluated to obtain data about workability is the ASTM C1437 Flow Table Test. After being placed inside the cone with a base diameter of 100 mm, an upper diameter of 70 mm and a height of 60 mm, the cone is pulled upwards and then the table is lowered 25 times by means of the arm under the table. The spreading diameters of the mixtures are determined by measuring the spreading diameters of the material spread on the table in different directions and taking the arithmetic average. Tay *et al.* [31] 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.

3.2.2.3 Buildability

Buildability is another essential parameter for a successful printing process. But there is no standard way to determine the buildability of concrete mix for 3D printer. The deposition of layers in the printing direction is a key criterion for production of concrete elements and structures by 3D printing. 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 [13], while other studies determined it by measuring the vertical settlement of printed layers [18]. According to Austin [32] buildability in 3D printable concrete is defined as the number of layers without significant deformation of the lower layers. In this study, the height of hollow concrete beams with 3 different internal patterns, printed in 10 layers with 2 different mixes, and the deformation in the layers were examined. Height measurements were made immediately after printing, and the same measurement was made again after the samples hardened.

3.2.2.4 Open Time

For cementitious mixtures, open time is usually related to setting time, which can be measured with a Vicat Apparatus. However, this device is designed to determine the initial and final setting time in characterizing the change in workability compared to fresh concrete [17]. Le *et al.* [33] have defined open time as the time period when the workability of fresh concrete is at a level where it can be extruded. They stated that the end of the workability period means the same as decreasing the workability, that is, increasing the difficulty of printing. The term open time is referred to as the time during which the material maintains ease of flow through the nozzle without any obstruction [34]. The most practical definition of open time comes from Chen *et al.* [35] it is defined as the period during which the material can be extruded smoothly without any discontinuation or disruption. In this study, Slump Test and Flow Table Test values of the prepared mixtures were examined successively at short intervals in order to obtain data about the open time. In the Flow Table Test, it was monitored how long the mixtures remained in the 15-19 cm range, which is called the printable region in the literature, and in the Slump Test, it was also monitored whether the mixtures moved away from the slump value at the first moment when taken from the mixer.

3.2.3 Testing of Hardened Concrete

Tests performed on hardened concrete specimens provide data on whether the mechanical properties of the mixtures are at the required standards. Strength tests are accepted as traditional quality data of concrete [36]. It is an important stage for performance evaluation in large-scale building elements made with 3D printers, 3D printed structures, and concrete works to be produced with 3D printers in the future. When necessary, it can provide guidance on issues such as improving print quality, optimizing mixtures, and increasing strength. In this study, the compressive strength test and flexural strength test of both mixtures for 3, 7 and 28 days were examined on 5 cm x 5 cm x 5 cm cube samples and 4 cm x 4 cm x 16 cm prism samples. In addition, 20 cm x 11 cm x 60 cm printed hollow concrete beams which have different infill patterns were tested for flexural strength. The point loading in the three-point flexural test on the printed hollow concrete beams was applied to the outer surface of the long side of the prism, not on the infill pattern in the printing direction.

CHAPTER 4
EXPERIMENTAL STUDIES

4.1 3D Concrete Printer

The most important point for the successful implementation of 3DPC technology, which is the subject of the thesis, is the 3DCP. The harmonious operation of all software, mechanical, technological, and electrical components of this 3DCP and ultimately the products produced by using concrete that can work in harmony with this 3DCP signify the successful completion of the project. The laboratory scale printer used throughout the studies was produced in the previous study at the Civil Engineering Laboratory of Gaziantep University and is within the Department of Civil Engineering. The mechanical design has been analyzed in detail to ensure accurate and continuous movement. Electronic design has undertaken the task of ensuring that the systems work in harmony with each other. Software developments have been made for the successful use of technology and management of this entire concrete printing process. The printing region limits of the printer used during the work are 1000 mm x 1000 mm x 1000 mm in the X, Y, and Z axes. The nozzle diameter, which is the final exit point of the concrete, is designed as 15 mm. There is a helix inside the extruder that facilitates concrete movement. Beams with 10 layers and dimensions of 600 mm x 200 mm x 110 mm were designed. Three different internal patterns were selected to be printed with a 3D printer. These internal patterns are called wave shape Fig-4.2(a), rectangular shape Fig-4.2(b), and parallelogram shape Fig-4.2(c) and the volume filling rates of the internal patterns of these shapes are wave-shape has 25% rectangular shape has 28%, parallelogram-shape has 50%.

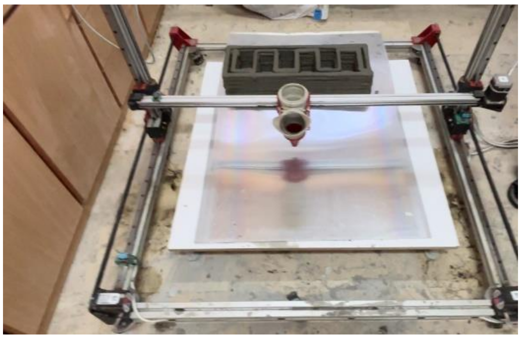


Figure 4.1 3D Concrete Printer (3DCP).

4.2 Preparation of Mix Designs

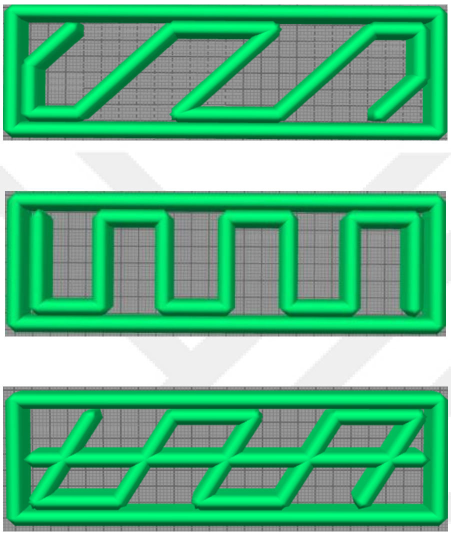
In this study, studies in the literature were examined and based on the reference mix designs, sand, cement, silica fume, fly ash, superplasticizer, and water were used to produce printable concrete as a result of preliminary trials. As a result of the preliminary test mixtures and the fresh concrete state tests applied to the preliminary test mixtures, two different designs of concrete mixtures were decided. 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 mixed for 1 minute. Superplasticizer was added to the remaining mixing water as recommended [28] 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 2 more minute and then the resulting concrete was taken from the mixer. The decided concrete mixtures, Mix Design-1 (M1) and Mix Design-2 (M2), are given in Table 4.1 and Table 4.2. Elements that failed in preliminary attempts during the printing process are shown in Fig-4.3(a), Fig-4.3(b), Fig-4.3(c).

Table 4.1 Mix Design-1 (kg/m^3),W/B Ratio: 0,40 (M1).

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

Table 4.2 Mix Design-2 (kg/m^3) ,W/B Ratio: 0,37 (M2).

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

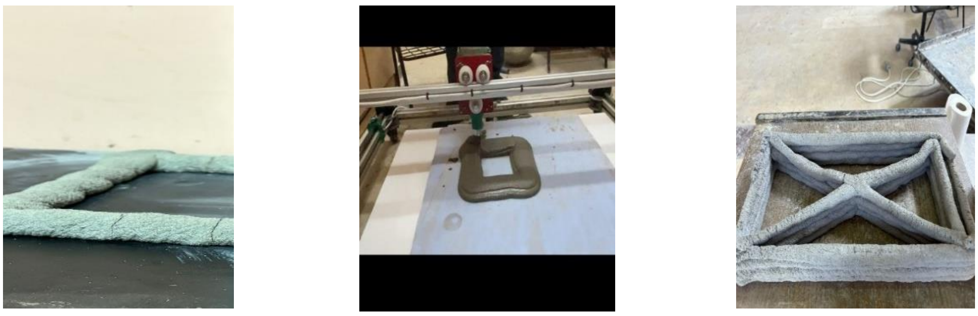


(a) Wave Shape

(b) Rectangular Shape

(c) Parallelogram Shape

Figure 4.2 Different internal patterns were designed.



(a) **(b)** **(c)**

Figure 4.3 Failed elements in preliminary attempts during the printing process.

4.2.1 Ensuring of Extrudability Conditions

While both mixtures were observed during extrusion, it was noticed that the nozzle maintained its shape, did not cause blockage in the nozzle, there was no segregation in the concrete mixture, and extrusion continued uninterrupted. Additionally, since there is a correlation between extrudability and flowability, it was desired to make the mixtures flowable without compromising their buildability, and this goal was achieved. As a result of visual observations and extruder and nozzle controls, both mixtures do not have any obstacles in terms of extrudability. An extrusion error where the flow is very difficult and interrupted is given in Fig-4.4.

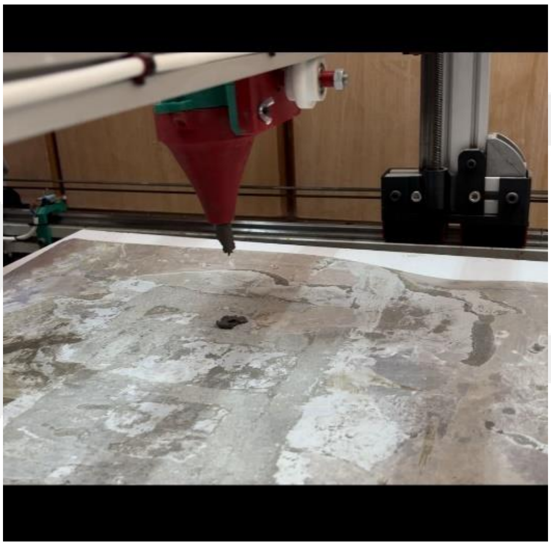


Figure 4.4 Inability to extrude.

4.2.2 Ensuring of Workability Conditions

ASTM-C143 Slump Test and ASTM-C1437 Flow Table Test were applied to check the workability of the mixtures. As a result of the ASTM-C143 Slump Test conducted in this study, it was seen that 2 mixtures obtained with M1 190 mm and M2 185 mm slump values could be printed. In order to add workability to the mixture, methods are being tried to reduce the shear strength of concrete by increasing the water/cement ratio of the mixture, adding superplasticizer to the mixture, and if there is an amount of superplasticizer, increasing it percentage compared to the cement [17]. In the ASTM C1437 Flow Table Test, another test evaluated to obtain an idea about workability, Tay *et al.* [31] It was mentioned in this study that it defined the printable region as a diameter value of 15-19 cm. As a result of the studies carried out to obtain mixtures with this diameter value, it was concluded that M1 and M2 mixtures are in the printable region. Mixtures with diameters below 15 cm almost block the nozzle and have difficulty in extrusion. Flow Table Test value of M1 has a diameter of 16.6 cm. Flow Table Test value of M2 has a diameter of 16 cm. A very high workability and flow occurs in mixtures with a diameter value above 19 cm, but buildability is not possible due to the consistency and intertwining and disappearing of layers. High workability problem was given in Fig-4.6. In the successful printing example, the Flow Table Test value of diameter is between 15-19 cm and the Slump Test value is between 180-190 mm. Fig-4.7.

(a) (b) (c)

Figure 4.5 (a) Representing Slump Test, (b) and (c) Flow Table Test

Figure 4.6 Very high workability causes problems.

Figure 4.7 The mixture meets the workability requirements.

4.2.3 Ensuring of Buildability Conditions

In this study, the heights of hollow concrete beams with 3 different internal patterns, printed with 2 different mixtures in 10 layers, and the deformations in the layers were examined. Height measurements were made immediately after printing, and the same measurement was made again after the samples hardened. As mentioned in the previous sections, in some studies, collapse distances in the layers and significant layer deformations were taken into account when reference was made to studies explaining buildability in different ways. Samples planned in 3 different internal pattern types with 2 different mixtures were successfully produced with a 3DCP. A total of 10 layers of 110 mm were prepared, each layer being 11 mm. In the measurements taken as soon as the printing process was completed, all 6 samples reached a total height of 110 mm, as planned. After all the samples were hardened, the measurement was repeated and the decreases in height were detected. Height decreases in mm size were observed, however, upon examining the layers individually, no visible or significant deformation was detected that would compromise buildability. Among the hollow concrete beam samples produced using M1, which initially measured 110 mm, it was measured that the parallelogram shape decreased to 105 mm after hardening, while the rectangular shape and wave shape decreased to 106 mm. When the hollow concrete beam samples produced using M2 were examined, it was observed that the parallelogram shape decreased to 107 mm, and the rectangular shape and wave shape decreased to 108 mm. Below is the height measurement graphic Figure-4.8 and Figure-4.9. Samples after printing and after hardening are shown in Figure 4.10 and Figure 4.11

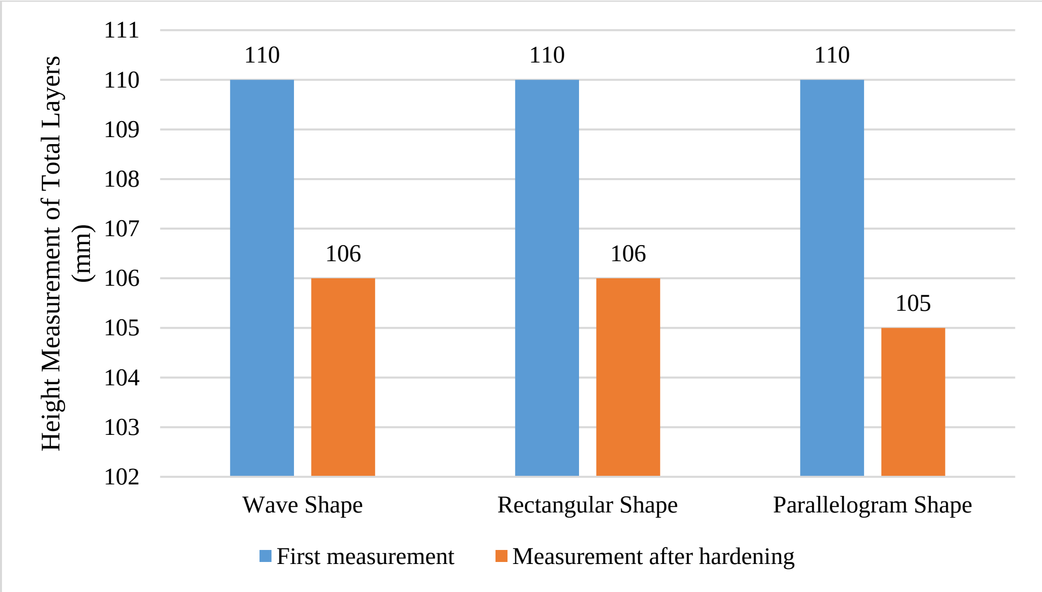


Figure 4.8 Total height measurement for M1 of hollow concrete beams

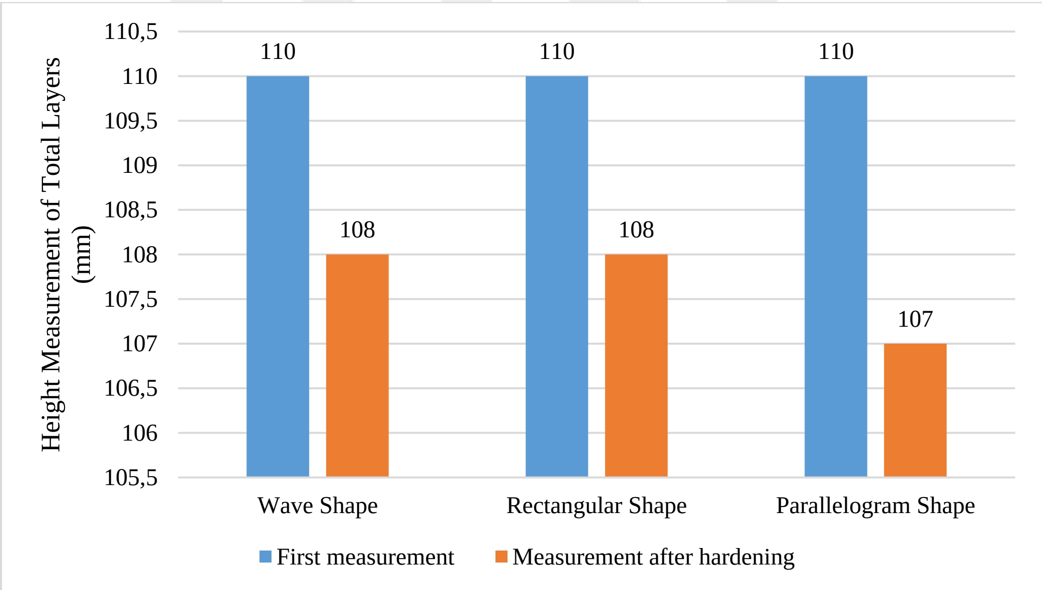


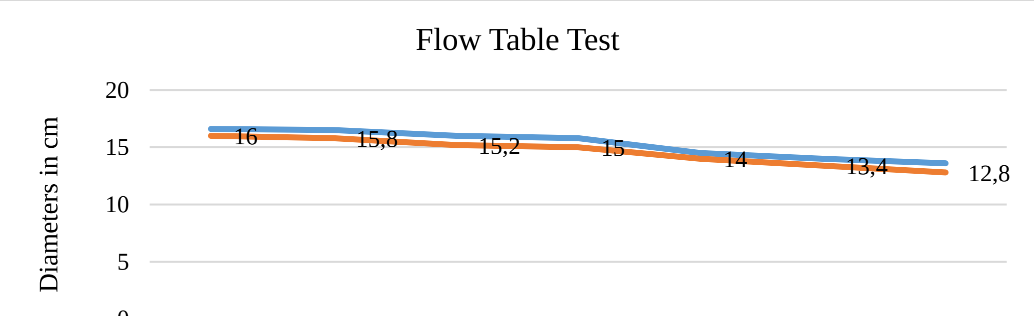
Figure 4.9 Total height measurement for M2 of hollow concrete beams

Figure 4.10 Fresh state height measurement.

Figure 4.11 Hardened state height measurement.

4.2.4 Ensuring of Open Time Condition

In order to benefit from the relationship between open time and printability of the mixture, a separate amount of the printable mixtures was excluded from the printing process and separate samples taken from this amount were subjected to both Slump Test and Flow Table Test at 5-minute intervals. The purpose here is to determine how far the mixture has moved from its original printable state over time, and therefore how long it takes for the workability of the mixture to no longer be at an extrudable level, the difficulty of printing increases, and discontinuous extrusion begins. In this measurement made for both M1 and M2, it was observed that there were decreases in Slump Test and Flow Table values in both mixtures after the 15th minute. It was determined that the Flow Table Test diameter value of 16.6 cm measured for M1 in the first minute decreased to 15.8 cm in the 15th minute. It was determined that this value decreased below 15 cm at the 20th minute. It was observed that the Slump Test value measured for M1 gradually moved away from the initially measured value of 190 mm, and with a visible change in the 20th minute, this value fell below 135 mm. When the measurements mentioned for M2 were made, it was determined that the Flow Table Test diameter value, which was initially measured as 16 cm, decreased from 16 cm to below 15 cm after the 15th minute. In the Slump Test measurement, it was observed that the initially measured value of 185 mm decreased to 120 mm at the 15th minute. It is seen that concrete workability is significantly lost within 15-25 minutes and extrusion becomes difficult. In practice, this situation creates the problem of blockage in the extrusion and transmission of concrete. Mixing the concrete which is printed with 3D printing technique is seen as an effective method to increase the workability time [17]. If the concrete mixture is continued to be mixed manually during the printing process after being taken from the mixer, or if it is gradually taken from the mixer and conveyed, which is a difficult practice, the workability time of the concrete mixture, that is, the open time, can be extended. It is possible to make explicit time adjustments without using a manual or automatic mixing system, which is applied after the concrete mixture is removed from the mixer [37]. The open time adjustment of the 3DPC mixture can be brought to the desired level by using setting accelerator or retarder additives [38].



	0th min	5th min	10 min	15 min	20 min	25 min	30 min
M1	16,6	16,5	16	15,8	14,5	14	13,6
M2	16	15,8	15,2	15	14	13,4	12,8

Figure 4.12 Change of Flow Table Test values over time.

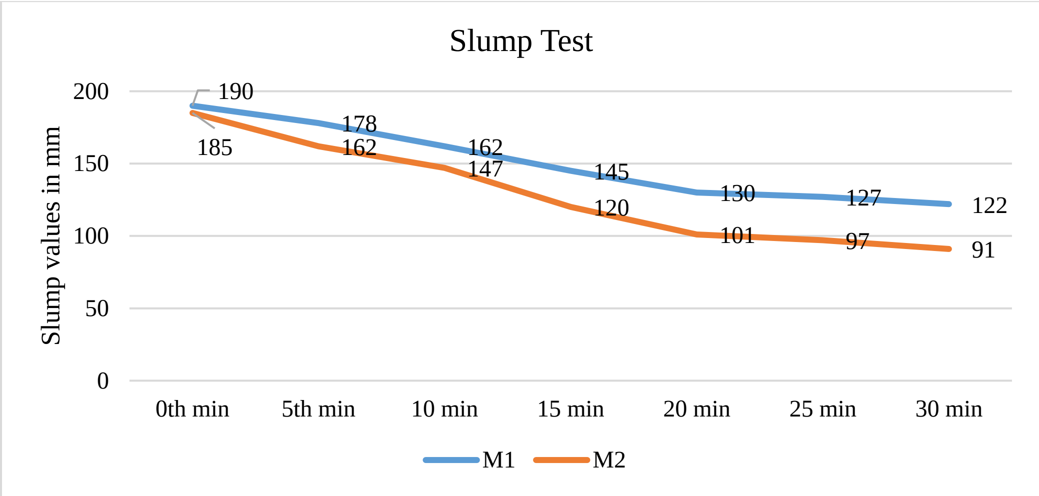


Figure 4.13 Change of Slump Test values over time.

4.3 Compressive and Flexural Strength of Samples

Several tests are applied to determine that the mechanical properties of the mixtures meet the required standards.

4.3.1 Compressive Strength of Samples

In this part of the study, ASTM C 109 the compressive strengths of the test specimens with dimensions of 5 cm x 5 cm x 5 cm for two mixtures were measured after completing the curing periods of 3, 7, 28 days.

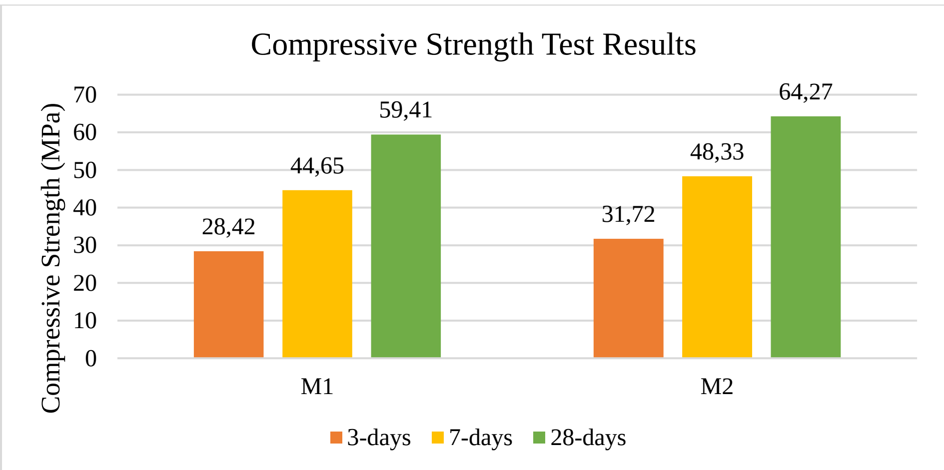


Figure 4.14 Compressive Strength values of 5 cm x 5 cm x 5 cm cubic samples.

Figure 4.15 Compressive Strength Test.

4.3.2 Flexural Strength of Samples

In this part of the study, ASTM C 39 the flexural strengths of the test specimens with dimensions of 4 cm x 4 cm x 16 cm for two mixtures were measured after completing the curing periods of 3, 7, 28 days.

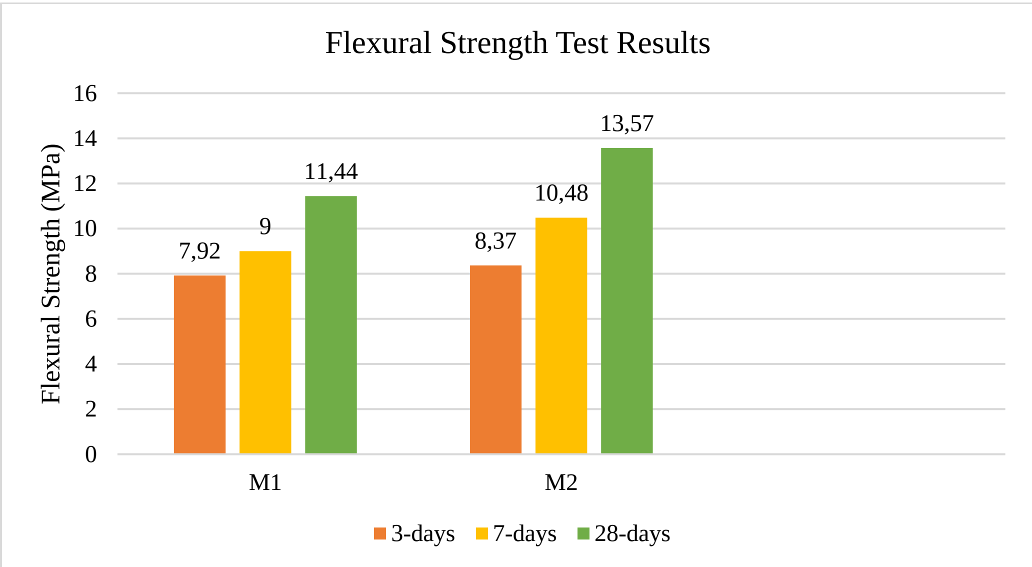


Figure 4.16 Flexural Strength values of 4 cm x 4 cm x 16 cm prism samples.

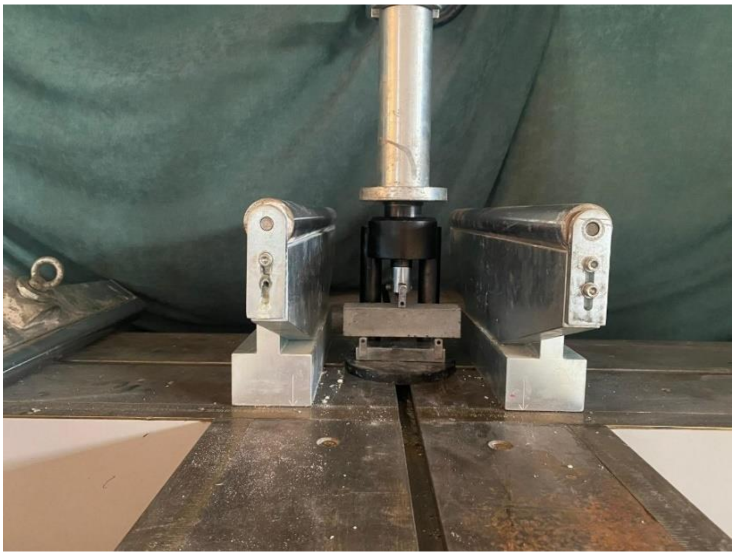


Figure 4.17 Flexural Strength Test.

4.3.3 Flexural Strength of Hollow Concrete Beams

In this section, the flexural strength of 20 cm x 11 cm x 60 cm 3D printed hollow concrete beams ,ten layers and each layer is 1.1 cm, with various infill patterns was tested for two mix designs. In the three-point flexural test conducted on the printed hollow concrete beams, the point load was applied to the outer surface of the prism's long edge(transverse), not in the layer deposition direction. As a result of the test, the maximum load that the hollow concrete beams were exposed to in the flexural test was determined.

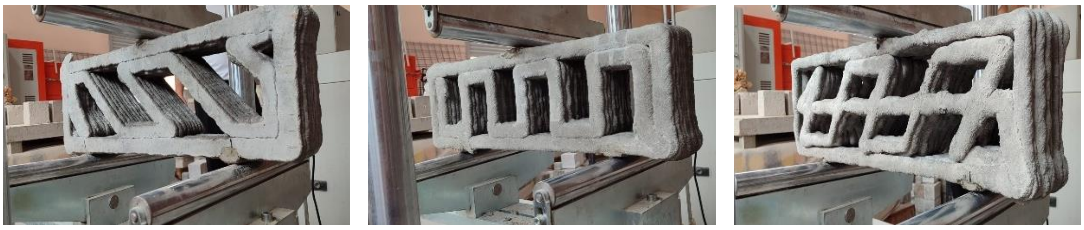


Figure 4.18 Flexural Strength Test of Hollow Concrete Beams

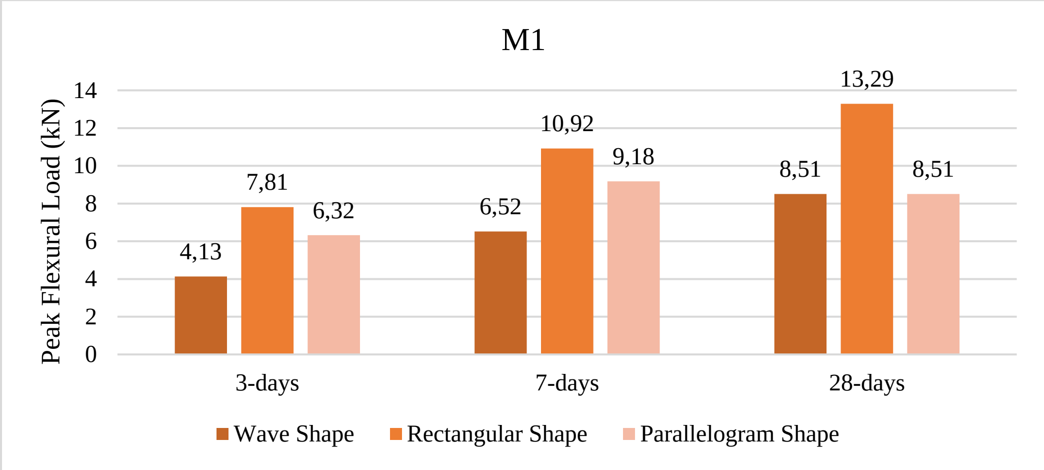


Figure 4.19 Peak Flexural Load of Hollow Concrete Beams for M1.

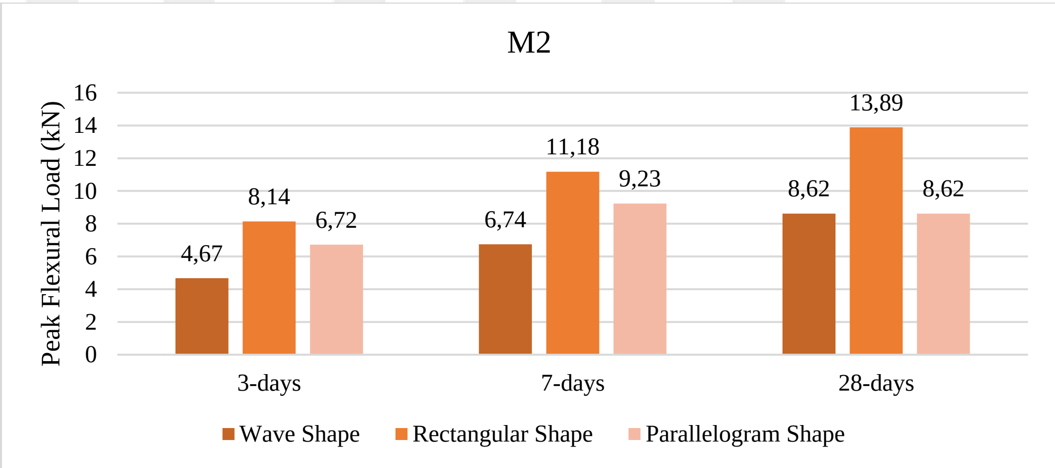


Figure 4.20 Peak Flexural Load of Hollow Concrete Beams for M2.

CHAPTER 5
RESULTS AND DISCUSSIONS

5.1 Fresh Properties of Mix Designs

As a result of the applied experiments, examinations, observations, and evaluations, it has been determined that the fresh properties of both mixtures meet the printable concrete requirements. 3DPC mixtures, which are different from traditional concrete mixtures, have important parameters such as extrudability, workability, buildability, and open time, as mentioned in the study. In this thesis, the extrudability condition based on the observations is met, indicating that there is no problem with extrudability in both mixtures, as they provide an uninterrupted flow during extrusion, do not create blockage in the nozzle, and the cycle continues throughout the process, which coincides with the studies in the literature. In the tests deemed appropriate for workability, which are actually among the traditional concrete tests, the shapes of complex geometry planned during the printing process were successfully printed. The workability of concrete mixtures is directly related to the high water/binder ratio, but it is observed that the mechanical properties of concretes with a high water/binder ratio are weakened [38]. In the study, the use of fly ash and superplasticizer was used to increase workability [39] without increasing the water/binder ratio too much. It has been determined that the created mixes remain in the region referred to in the literature as the 'printable region of 15-19 cm, [31]' with M1 having a Flow Table diameter value of 16.6 cm and M2 having a value of 16 cm. The issue of buildability, defined in different ways in some studies, is defined in its simplest form as the ability of extruded layers to maintain their smooth geometry without deterioration under the weight of the layers added on top of them. Data regarding hollow concrete beams carried out in laboratory studies were shared in the study. It is confirmed by the data that the beams printed at the point of buildability do not pose any problems regarding this situation. For both mixtures, there were no problems such as visible deformations or not preserving the geometry between the layers of the printed hollow concrete beams. In the hollow concrete beam samples produced for M1 and having a 50% volumetric filling rate, which means the highest weight, the height loss in the parallelogram shape was measured as 4.5%, while the rectangular shape with 28% filling rate and the wave shape with 25% filling rate were measured as 4.5%. The figure experienced a height loss of 3.6%. When these shapes were examined for M2, the height loss of the parallelogram shape was measured as 2.7%, while the rectangular shape and wave shape experienced a loss of 1.8%. It was observed that the parallelogram shape, which has the highest weight due to its volumetric filling, was the internal pattern that suffered the most height loss for both mixtures because the layers below had to carry a heavier load than other internal patterns beams, and the height loss was greater for M1. It is thought that the lower height losses in M2 are due to the lower W/B ratio and the increase in mineral additives and also the fact that the Flow Table diameter value for M1 is 16.6 cm, while this value is 16 cm for M2 is thought to be effective in the layers flowing on top of each other and creating crush between themselves.

Figure 5.1 Hollow concrete beams of M1 and M2 before measuring their heights.

The concept of open time, which is associated with the printability of the elements, is defined as the period during which the concrete maintains its workability and extrudability. The fact that this time is short for a mixture creates a problem for printing elements that require a lot of material on a large scale. The fact that workability decreases over time, extrusion becomes difficult, and even causes blockages in the nozzle and transmission channels is directly related to the concept of open time. In this study, this concept, which is associated with Slump Test values and Flow Table diameter values, is expressed by checking whether the mixtures have moved away from printability by re-applying the tests at 5-minute intervals. During repeated experiments, it was observed that both mixtures showed resistance to printing starting from the 15th minute. According to the inferences made from preliminary studies in the laboratory and studies in the literature, chemical additives, accelerators or retarders can be used to increase the open time to the required level. In addition, manual or simple automatic mixing after the mixture is taken from the mixer also extends the open time.

5.2 Mechanical Properties of Samples

Compressive strength, which is linked to some mechanical properties of concrete such as Young's modulus, flexural capacity and flexibility, has become an important material property as it is also used as a traditional control parameter of concrete quality [36]. Considering the compressive strength of the 5 cm x 5 cm x 5 cm cube samples examined in this study, the strength value reached by the sample as a result of 3-days curing for M1 was 28 MPa. When the 7-days cure period was left behind, this value increased by 57.14% to 44 MPa, and finally at the end of the 28-days cure period, it reached 59 MPa, an increase of 110.71% compared to the 3-days cure period. When these values were examined for M2, it was determined that 31 MPa compressive strength was reached at the end of the 3-days curing period. At the end of the 7-days curing period, it was observed that a 54.8% increase was reached to 48 MPa. Finally, when the 28-day curing period was left behind, the compressive strength value reached 64 MPa, an increase of 106.45% compared to the 3-days sample. The increase in three-point flexural strength test values of 4 cm x 4 cm x 16 cm prism samples was also followed. For M1, the flexural strength value reached at the end of the 3-days curing period was 7.92 MPa. At the end of 7-days curing, this value increased by 13.6% and reached 9 MPa. When the 28-days cured sample reached the end of the curing period, it increased by 44.4% and reached 11.44 MPa compared to the 3-days cured sample. When these values were examined for M2, the flexural strength value of the prism was measured as 8.37 MPa as a result of 3-days curing. The flexural strength value of the

7-days cured sample became 10.48 MPa, an increase of 25.6%. When the 28-days cured sample reached the end of the curing period, it increased by 62.12% and reached 13.57 MPa compared to the 3-days cured sample. When the two Mix Designs were compared among themselves, M2 showed 10.7% higher compressive strength value in 3-day samples. This parameter is 9.09% in 7-day samples and 8.47% in 28-day samples and also M2 showed 5,68% higher flexural strength value in 3-day samples. This parameter is 16,4% in 7-day samples and 18,61% in 28-day samples.

All beams show brittle fracture process. This may be because the printed beams are not reinforced with steel rods or fiber. The majority of cracks in the hollow concrete beams begin at the point where the filament makes contact with the bottom edge. Different internal pattern may cause different crack propagation path. During the bending process of the printed beam sample, the bottom part is subjected to important tensile stresses. Cracks will appear when the tensile strength is reached. For M1, when hollow concrete beams were compared based on the maximum flexural load until failure, the rectangular shape outperformed the parallelogram shape by 23.5% among 3-day samples. Compared to the wave shape, it resisted 89% more flexural loading. Likewise, when looking at 7-day samples, the rectangular shape has better performance than the other two hollow concrete beams. In 7-day-old samples, the rectangular shape was able to resist 18.9% more flexural load than the parallelogram shape. Compared to the wave shape, the rectangular shape showed 67% better performance. When it came to 28-day samples, the rectangular shape withstood 9.47% more load than the parallelogram shape without failure. The rectangular shape was able to resist 56% more flexural load compared to the wave shape. For M2, when hollow concrete beams were compared based on the maximum flexural load until failure, the rectangular shape outperformed the parallelogram shape by 21.13% among 3-day samples. Compared to the wave shape, it resisted 74.3% more flexural loading. Likewise, when looking at 7-day samples, the rectangular shape has better performance than the other two hollow concrete beams. In 7-day-old samples, the rectangular shape was able to resist 21.12% more flexural load than the parallelogram shape. Compared to the wave shape, the rectangular shape showed 65.87% better performance. When it came to 28-day samples, the rectangular shape withstood 8.43% more load than the parallelogram shape without failure. The rectangular shape was able to resist 61.13% more flexural load compared to the wave shape. In Figure-5.2 Different internal pattern and different crack propagation path.

(a)

(b)

(c)

Figure 5.2 Different internal pattern and different crack propagation path.

CHAPTER 6
CONCLUSION

Nowadays, when automation and technology have entered every aspect of life, it is inevitable that this change will also occur in business sectors. 3D printers, whose use is increasing day by day in aviation, jewelry, healthcare, textiles and food, have also begun to be used in the construction industry. This technology, which causes different approaches to be considered in architecture and civil engineering, has been the subject of multiple aspects, both in R&D studies within the scope of laboratory conditions, in academic studies, and in the field of production. Important points such as the production of large-scale structures, printing of structural elements, optimization of elements with complex geometries, and optimization of concrete mixtures are still being researched. Machinery, software and electronic research and development work continues within 3D Concrete Printers. Issues such as nozzle diameters and shapes, printing speed, movements in the axes, and the service life of the machines are just some of the research topics within 3DCP devices. In this study, the printability of beams with different patterns in the dimensions of 200 mm x 110 mm x 600 mm was examined with a laboratory-scale 3DCP with a movement distance of 100 cm in the X, Y, Z axes. It has been investigated to meet the requirements required for printing. Compressive strength values of the concretes created as a result of the mixture designs were also determined in 50 mm x 50 mm x 50 mm cubes and flexural strength values in 40 mm x 40 mm x 160 mm prisms. As explained in the study, both of the mixtures called M1 and M2 met the requirements of being printed on a 3DCP as a fresh state feature. The fact that there is no blockage in the nozzle during the extrusion process and that the exiting concrete does not lose the shape of the nozzle has shown that it ensures extrudability. With both mixtures in the printable region, 110 mm high hollow concrete beams could be manufactured in 10 layers, showing that there were no problems in terms of buildability. It has been observed and reported that the loss in height of the beams produced with the relatively lighter mixture of the 2 mixtures, called M2, is less. And again, when height losses are taken as a criterion, it has been observed that there is less collapse in the wave shape, which is 25% volumetric filled, and the rectangular shape, which is 28% volumetric filled. M2 is slightly lighter than M1 (1.61%), its water/cement ratio is relatively slightly lower (0.37) and its flow table value is relatively slightly lower (16 cm) is thought to cause less collapse. In the study on open time, it was observed that the mixtures started to lose their printable properties after the 15th minute, but as mentioned in the literature, it was seen that the open time could be brought to the desired level with chemical additives, setting accelerators or setting retarders. Although M2 gives more positive results, M1 also provides the printable feature. When looking at the mechanical properties of concrete in its hardened state, it can be said that the final strength properties of M2 give better performance than M1. When the compressive strengths were examined, it was seen that M2 showed higher values in the 28-day samples as well as in the 3-day and 7-day samples. In 28-day samples, M2 has 8.47% higher compressive strength value. M2 also gave better results in 40 mm x 40 mm x 160 mm prisms where flexural strengths were examined. Likewise, as in the 3-day and 7-day samples, the flexural strength values in the 28-day samples were higher for M2. M2 gave an approximately 18% higher flexural strength value compared to M1 in 28-day samples. When 3 different types of beams printed with both mixtures in different geometries are examined, it can be said that M2 gives better results. For both mixtures, the load that the rectangular shape withstood until failure was higher than the other beams. M2 Compared to M1 for the 28-day rectangular shape, the rectangular shape printed with M2 gave 4.5% better performance withstanding the peak flexural load of 13.89 MPa. What is remarkable in this regard is that although the volumetric filling rate of the parallelogram-shaped beam (50%) was higher than the volumetric filling rate of the rectangular-shaped beam (28%), the rectangular-shaped beam was able to resist more loads than the parallelogram-shaped beam in both mixtures. When looking at the wave-shaped beam, it was seen that it resisted less load than the other two hollow beams for both mixtures. Here too, it is thought that the geometry, that is, the internal pattern, is effective in the load carrying capacity. As a result of all these studies, it appears that the fresh and hardened concrete properties of mixtures working in harmony with 3DCP produced on a laboratory scale enable the production of elements in complex geometries. The small nozzle size is due to the small 3DCP size. Due to the small nozzle size, coarse aggregates and fibers could not be used in the mixtures. In other words, in future studies, it will be possible to make mixtures reinforced with aggregates and fibers, with larger sized machines and therefore larger sized nozzles, and concretes with higher mechanical properties can be obtained due to these materials used. Complex geometrical designs can be produced with these concretes. This study on this subject in the field of civil engineering, which does not yet have standards, is at a point where it can give ideas for future studies on complex geometries, mixture designs, and laboratory scale 3D printers.

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CURRICULUM VITAE

FURKAN BORAN AKKOYUN

EDUCATION

Bachelor of Science: Gaziantep University, Civil Engineering Department

Master of Science: Gaziantep University, Graduate School of Natural and Applied Sciences, Mechanic Sciences

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