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Advances and Current Trends in 3D Concrete Printing for Engineering Structures

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Abstract – In recent years, with advancing technology, the need for human labor has decreased in various sectors, and robots have taken over almost every stage of production. Particularly, the three-dimensional (3D) concrete technology that is emerging in the construction sector and gaining popularity day by day can be seen in urban furniture, various decoration products, home and office production, and even bridge examples. Research and applications show that 3D concrete is preferred over traditional concrete in many aspects due to its advantages. In the future, the advantages of 3D concrete technology, such as being more cost-effective than traditional concrete, faster production, high strength due to the concrete class, minimal need for human labor, and ease of production, will make it more preferred. While there are only a limited number of structures in the world produced entirely using 3D concrete technology for transportation infrastructure, there are no examples in our country yet. The aim of this study is to determine the advantages of 3D concrete technology based on scientific data and to examine examples of its use in road engineering structures. Since a significant part of the construction sector constitutes the transportation sector, the usability of 3D concrete technology in transportation is also discussed. As a result of the study, it is concluded that there are already examples of 3D concrete technology for road transportation engineering structures, especially bridges. Since this technology is still relatively new and not widely used, future project examples for its use in transportation have been explored.

Keywords – 3D Concrete, 3D Printer, Engineering Structures, Pedestrian Walkway, Bridge

I. Introduction

3D printing technology, referred to as a new industrial revolution worldwide, involves the creation of three-dimensional objects through the combination of various materials in specific proportions, with the support of coding and software. 3D printing technology has a very broad range of applications, and it continues to evolve and expand its usage in various fields, including the construction industry.

Also known as 3D printing, it offers advantages over traditional construction technology, including higher building efficiency, lower labor costs, and reduced construction waste. 3D printed concrete is a special type of concrete that can be deposited layer by layer using a 3D printer without the need for traditional formwork and vibration processes. Important performance indices, such as workability, curing, curing time, and mechanical properties, can be optimized through material selection and printing parameters. To date, many building structures have been successfully printed using 3D printed concrete technology, and some have even reached real-world applications. 3D printed concrete holds significant potential for applications in low-income countries, such as affordable housing construction [1]. While 3D concrete printing is not yet widespread in Türkiye, there are only two companies engaged in its production. The first company to use 3D concrete technology is ISTON, followed closely by Sika.

II. The Turkish Market

İSTON was established in 1986 with the aim of understanding the infrastructure and superstructure needs of the city and providing quality solutions, by the Istanbul Metropolitan Municipality. İSTON exports its products not only in Istanbul but also in other cities of Türkiye. It also engages in exports to different countries. In addition to manufacturing concrete and reinforced concrete pipes, paving stones and curbstones, ready-mix concrete, prefabricated building elements, and urban furniture (Fig. 1), It also provides architectural design, urban project implementation, contracting, and construction inspection services. It aims to facilitate the use of 3D printers, which have made significant progress in many sectors today, in the construction industry and develop concrete suitable for use with 3D printers that differ from traditional concrete. This production technology offers advantages over molded manufacturing technology, such as enabling faster production, requiring less labor, and allowing production without the cost of molds.

Fig. 1 Urban furniture produced with a 3D concrete printer [2].

A. *3D Concrete Printer*

They aim to promote the use of 3D printers in the construction industry and has developed its own 3D concrete printer for this purpose. Their goal is to create concrete that is compatible with 3D printers, which differs from traditional concrete. This manufacturing technology offers several advantages over moulded manufacturing technology, including faster production, reduced labour requirements, architectural flexibility, and lower costs due to the absence of mould expenses [2]. The 3D printer (Fig. 2) has legs that are 160 cm tall and a height of 3 meters. If the legs of the printer are extended, it can produce larger-sized products.

Fig. 2 3D Printer [2]

The robot has its own CAM (Computer-Aided Manufacturing) program that can create drawings in various formats. The data extracted from the drawing is transferred to the CAM program, which then slices the data and enables layer-by-layer printing.

B. *Mobile Plant*

To enable production at the planned location of the structure, a mobile plant is utilized. Since the ink for the printer is concrete, it is necessary to feed the printer with concrete. Consequently, there is a greater need for a larger quantity of concrete for rapid production. To meet this demand, a mobile plant has been developed (Fig. 3).

Fig. 3 Mobile plant [2]

Due to the presence of various chemical additives in the concrete used and the differences in setting behaviour, strength behaviour, and early-age strengths, it is necessary to produce the 3D concrete mortar on-site. Within the printer, there are compartments for holding dry materials, cement, and aggregates. As with all aspects, the mixing process differs from regular concrete. There are two mixers: one where the concrete is made, and then it is transferred to the other and pumped from below. This way, the mortar can be used immediately in production without being damaged or losing its properties. The entire process can be controlled by computers. This process, known as mobile plant automation, can be monitored by operators.

C. *Technical Specifications of 3D Concrete*

The compressive and flexural strengths of the 3D concrete using white cement and grey cement are as follows:

- 3D Concrete (White Cement):
Compressive Strength (28 days): 60 MPa
Flexural Strength (28 days): 10 MPa
- 3D Concrete (Gray Cement):
Compressive Strength (28 days): 45 MPa
Flexural Strength (28 days): 8 MPa
- The sound transmission class (RW) for both types is 45.3 dB.
- The thermal conductivity value (λ) for both types is 0.74 W/m²K, and the thermal resistance value (R) is 0.078 m²·K/W.

D. *Comparisons with Traditional Concrete*

3D concrete eliminates the costs associated with masonry, plaster, and insulation due to its construction without these elements. In this aspect, it offers an advantage over traditional concrete once again. It is known that 3D concrete meets standard values without the need for additional insulation and, thanks to the technology they currently use, it provides a 20% cost savings in rough construction. While ten workers are employed in the construction process with traditional concrete, the 3D concrete technique requires a total of three people. One person operates the robot thanks to this technology, and two people are needed for concrete preparation. In the 3D concrete technique, there is no need for lightweight bricks used in the traditional concrete method. A comparison of cube compressive strength and flexural strength between lightweight concrete, traditional bricks, and 3D concrete is shown in Table 1.

Table 1. Strength Comparisons [2]

Characteristics	**Lightweight Concrete Brick**	**Traditional Brick**	**3D Concrete**
Cube Compressive Strength (MPa)	3.5 – 5.0	5.0 – 6.0	50.0 –60.0
Flexural Strength (MPa)	-	-	8.0 – 9.0

E. *Construction Site Conditions*

Since the concrete printing process will take place at the construction site, certain conditions need to be met. During production, the product should be covered with tents or shelters. There should be no rain during production, and the product should not be exposed to excessive sunlight. Additionally, excessive wind and the inability to block it can lead to cracks in the walls.

III. 3D CONCRETE IN ENGINEERING STRUCTURES

A. *Bicycle Bridge (Netherlands)*

The bridge is part of the renovation of the existing bicycle path called Lieve Vrouwensteeg in the village of Gemert, Netherlands. It spans over a small local canal named Peelse Loop. The bridge has a span of 6.5 meters and a width of 3.5 meters. The uniformly distributed design load (qEd) is 5.0 kN/m². The realization of the printed bridge is part of a project involving government, industry, and Eindhoven University of Technology (TU/e) from the outset. The bridge is designed taking into consideration the capabilities of the 3D concrete printer at TU/e. It consists of printed elements that are rotated 90° after printing and then compressed together with post-tensioned tendons. Fig. 4 illustrates the design concept. The final cross-section of the bridge is 3440 × 920 mm. Structural calculations have shown the need for sufficient shear capacity due to the relatively low tensile strength of the concrete used [3].

Fig. 4 Conceptual Design of the 3D Bicycle Bridge [3]

The printer can print elements up to 2.8 meters in height. The bridge sits on two traditional abutments with pile foundations due to soft ground conditions. A steel parapet extends along the entire length of the bridge and is supported independently of the printed bridge. Considering the prestressing force, the bending moment resistance is governed by the prestressing force, making compressive strength particularly important for this project. To resist external shear forces, knowledge of the concrete section's shear resistance is necessary. The design includes embedded reinforcement cables that can serve as stirrups. In addition to strength, the stiffness of the concrete must also be known (Table 2). Under prestress, the structure shortens. The amount of shortening depends on the section's stiffness, and therefore, the sectional area and elastic modulus.

Table 2 Structural Properties of the Printing Mix Used in the Structural Design of the Bridge [3]

	Age	Value
Density	28 days	2,000 kg/m^3
Elastic Modulus	28 days	19,000 MPa
Average Compressive Strength	28 days	23.2 MPa
	28 days	21.5 MPa
	28 days	21.0 MPa
Average Tensile Strength	28 days	1.9 MPa
	28 days	1.6 MPa
	28 days	1.3 MPa
Creep Factor	7 days	1
	14 days	2.5
	56 days	3
Shrinkage	7 days	0.6
	14 days	1.2
	56 days	1.5

B. *The World's Longest Printed Bridge*

In the Netherlands, Saint-Gobain Weber and its partners have constructed the world's longest 3D printed concrete pedestrian bridge (Fig. 5). Saint-Gobain Weber won the "Bridge Project" in partnership with BAM, a Dutch construction company. Designed by architect Michiel van der Kley at the request of Rijkswaterstaat (the Dutch government agency responsible for the construction and maintenance of public infrastructure), the structural engineering was carried out by Witteveen+Bos, and parametric modeling was done by Summum Engineering [4]. Van der Kley successfully designed the bridge to absorb different forces at various locations and provide a more personalized touch, without being limited by traditional processes such as material choices or concrete moulds.

Fig. 5 The world's longest 3D printed bridge with a span of 29 meters [5].

To realize Van der Kley's vision, Witteveen+Bos converted the bridge's design into 3D printable structural components. Based on this data, a parametric model created by Summum Engineering was used to generate the final design of the bridge. The model took the original design and broke it down into a series of structurally constrained sections, optimizing the internal geometry for the bridge based on the printing capabilities developed by TU Eindhoven. Once the design of the bridge was completed, construction began at Weber Beamix's concrete printing factory in Eindhoven. The bridge was printed using BAM's concrete 3D printing technology and then assembled on-site. It is known that the 29-meter-long bridge holds the title of the world's longest 3D printed concrete pedestrian bridge. 3D printed bridges can be constructed much faster and require less concrete compared to traditional methods. According to the project partners, these factors, along with the sustainability and design freedom offered by concrete 3D printing technology, make it an attractive technique for future construction projects.

C. 3D Concrete Printed Bridge (Shanghai)

A team led by Professor Xu Weiguo at the School of Architecture, Tsinghua University in Beijing, has constructed a 26.3-meter-long concrete bridge using 3D printing (Fig. 6).

Fig. 6 3D Printed Bridge (Shanghai) [6]

The bridge was designed by the Zoina Land Joint Digital Architecture Research Center at Tsinghua University School of Architecture and built by Shanghai Wisdom Bay Investment Management Company [6]. This single-arch bridge was constructed using 176 concrete units printed with a two-armed robotic 3D printing system. All components were printed within 450 hours [7]. The structure of the bridge comprises 44 voids, and the deck is filled with white gravel in the form of "brain coral." The handrails are made up of 64 pieces. All components were printed using a compound consisting of polyethylene fibre concrete and additives [7]. Research Center reports that the cost of this bridge is only two-thirds of that of a similarly sized traditional bridge. The primary reason for this cost savings is the absence of any templates or reinforcing bars in the printing and construction of the bridge, resulting in significant cost reductions. The bridge also features a monitoring system to track how the concrete deforms over time. This data will be used to further enhance the use of 3D printing in engineering.

IV. CONCLUSION

3D printing and 3D concrete printing technology, which are constantly evolving, have garnered worldwide attention due to the wide variety of products they produce and the use of high-strength concrete (C50-60). Compared to traditional concrete and traditional construction, 3D concrete printing offers significant cost and delivery time advantages. When considering advantages such as the reduced need for labour during the construction period regardless of the type of structure, the absence of formwork costs, and the architectural flexibility it provides, 3D concrete printing emerges as a promising construction method to enhance productivity and efficiency in the construction process.

In recent years, 3D concrete printing technology has been used for commercial buildings, several bridge constructions, and engineering structures in transportation. Currently, there are many examples of structures produced using 3D technology, such as houses, offices, and bridges. When looking at the past, present, and future projects of this technology, it is safe to say that the goal of every new project is to be the "biggest" and the "first." For example, the desire to make each bridge project longer and larger than the previous one can be interpreted by examining past project examples. The competition among companies to be leaders not only increases competition but also allows for the development of 3D concrete printing technology.

While it can be said that 3D printing technology is not as widely used in engineering structures as in residential and office buildings, by looking at the examples of bridge projects and the 3D concrete printing dam project planned for completion in 2024, it can be predicted that there will be a wide variety of products in this field as well. In fact, it can be concluded that 3D concrete printing technology will replace traditional concrete in almost all types of structures in the near future.

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