Durability of 3D-Printed Concrete as Permanent Formwork for Reinforced Concrete Structures

Win Ko Ko Htet[1,] Totsawat Daungwilailuk[1,*] Kamonpun Jansang[1] and Atchara Sonrod[1]

[1] *Department of Civil & Environmental Engineering, Faculty of Engineering, Mahidol University, Nakhon Pathom, THAILAND*
[*]*Corresponding author; E-mail address: totsawat.dau@mahidol.ac.th*

Abstract

The construction industry is undergoing transformative sector with the advancement of Three-Dimensional Concrete Printing (3DCP). This technology offers numerous advantages that encompass reduction in labor costs, minimization in construction waste, and enhancement in construction duration. This study investigates the durability of 3DCP when used as permanent formwork for reinforced concrete (RC) structures, by focusing on chloride penetration and porosity effect. A total of 9 testing specimens that are 15cm x15cm x 15cm dimensions were prepared for both types of concrete at the age of 28 days. Six of the specimens were tested and collected data (3 specimens for casted concrete and 3 specimens for 3DPC) for chloride penetration test by submerging in 3% concentration of sodium chloride solution. Chloride penetration depth was measured and evaluated the durability results between 3DPC and conventional casted concrete. Moreover, compressive strength testing was performed for conventional concrete by using three testing samples. By examining the durability of 3DPC as permanent formwork in reinforced concrete construction, this study will offer the potential of utilizing 3DPC as alternative advanced construction material.

Keywords: Three-Dimensional Printed Concrete(3DPC), Chloride Penetration, permanent Formwork

1. Introduction

Construction is the one of the main contributors for developing economic growth, transportation, infrastructure, and urban development. Globally, $14.4 trillion is used in the construction sector, that is around 14.2% of Global Gross Domestic Products. However, the construction industry has experienced notably low productivity compared to other sectors while those sectors have used digital and automated technologies for more than a decade.

Enormous natural resources are utilized for reinforced concrete construction as the fulfillment of required demand that cannot be fully recycled. Approximately 8% of carbon dioxide is produced globally. As a result, it can highly impact the ecosystem of the natural environment and lead to global warming. Energy efficiency and environmentally friendly construction are recently popular to balance between human and natural environment for long-term sustainability. To minimize this effect, automated modern reinforced concrete engineering technology called Three-Dimensional Concrete Printing (3DCP) is developed for the construction industry.

3DCP is a layer-by-layer extrusion of concrete by using 3D printer. It is still developing technology, and it is very significant to continue investigation in the civil engineering industry. This technology will also promote environmental sustainability, reducing material waste, quality assurance and control, on-site and off-site manufacturing, hybrid construction. By using 3D printing technology, it allows the whole building to construct, especially low-rise structures, bridges and complex parts of building components that are difficult with traditional formwork system. But it still needs to do extensive research material consistency, structural integrity, resilience, and long-term durability to operate efficiently under extreme conditions.

3DCP is also applicable as permanent formwork for reinforced concrete structures. Due to its dense microstructures and precise material placements of 3DCP technology, it can reduce the pathways to infiltrate aggressive chemical agents under extreme environmental conditions. Using 3DPC as permanent formwork can significantly mitigate chloride penetration effects by ensuring durability, longevity, resilience and sustainability of reinforced concrete structures. Previous research also studied the durability of 3D printed concrete as permanent formwork with various material proportions, additives, and admixtures.

Due to the influence of chloride penetration, hydraulic cement was used to investigate durability. In this research, 3DPC is used as permanent formwork compared to traditional concrete technology under wet-dry cycles by submerging 3% of sodium chloride solution. It is expected to provide a reference for the future potential of structural degradation due to chloride penetration. Cooperating with 3DPC as permanent formwork and post-cast concrete composite can promote durability and sustainability for the future construction industry.

2. Literature Review

2.1 3D concrete printing as permanent formwork system

Formwork plays an important role for the construction project to shape the proposed structural integrity as temporary molds. Construction Industry generally relies on using traditional plywood formwork systems. For assembling formwork, it generates unrecyclable waste that can impact environmental sustainability. The formwork process involves around 30 to 60% of total construction cost. It also takes 50 to 70% of the production time for the whole construction. As a traditional formwork system uses large number of labor and materials, it uses 50 to 60 % of total construction cost.[1] To adopt these concerns, 3D concrete printing technology has been developed.

Placzek & Schwerdtner [2] found that as 3DCP is directly printed by using a 3D printer with formwork less system, it can accelerate hardening rate that can affect bonding between each layer and post-cast concrete for the permanent formwork system. Due to the design flexibility of 3D printed concrete, it is applicable as permanent formwork and rebars can also be placed to achieve optimum performance according to the current building codes, standards and regulation. Although it is applicable as permanent formwork, it is significant to ensure the bonding performance between 3DCP and post-cast concrete composite. Chang et al [3] investigated that Interfacial bonding properties especially decrease under wet-dry cycles and heat-cool cycles by increasing structural deterioration of the building. Fan et al [4] studied that debonding failure between 3DCP and post cast concrete is due to the tensile strength that is perpendicular to the interfaced caused by shrinkage and external load.

2.2 Rheological properties

Rheological properties mean flowability and deformation behavior of fresh concrete under applied load. As 3D printed technology constructs buildings without using any additional formwork by extrusion subsequent layer, the bottom layer must be ensured to support its own weight without excessive deformation or collapse. During extrusion the viscosity of 3DCP must be less and regain viscosity after deposition to maintain its shape. All the printing process followed as shown in Fig. 1. This promotes layer adhesion between layers and improves durability. Zhang et al., [5] studied optimized rheological properties improved layer adhesion to reduce voids and shrinkage cracks that have great potential for chloride penetration.

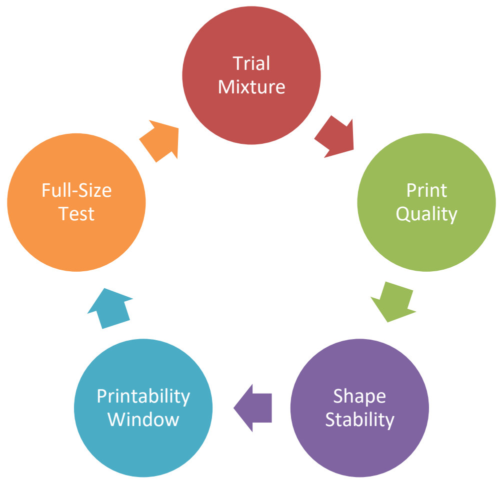

Fig. 1 Proposed framework for Printing Process

2.3 Interfacial bonding between 3DPC and post-cast concrete composite

Wang et al [6] studied the interfacial bonding properties between 3DPC and post-cast concrete by setting each layer height 10mm, 15mm and 20 mm. Prepared 3DPC were cured 1 day, 3 days, 7 days and 14 days respectively by using water spraying and film coating. At the designated curing ages, normal concrete was cast and cured for 28 days. This study used sulphate aluminum cement for 3DPC and ordinary Portland cement for cast concrete. Interfacial bonding split tests were performed at the specific age of 3DPC and post-cast concrete.

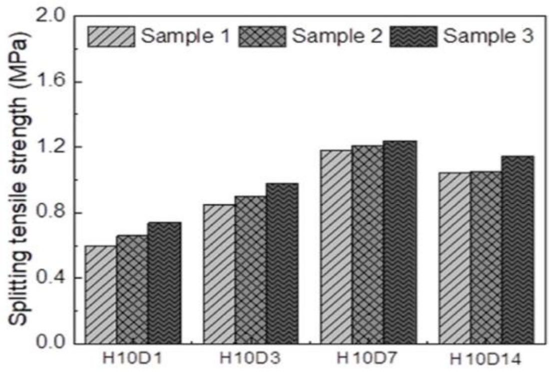

Fig. 2 Splitting bonding strength of samples of printing layer 10mm [6]

Among the different cast ages, the best performance date for interfacial bonding date is 7 days as described in Fig. 2. According to this research, the interfacial bonding test decreased at 28 days.

2.4 Effect of chloride penetration under wet-dry conditions

Durability is a crucial aspect for both 3D printed concrete and normal concrete. Providing adequate cover and using high-performance concrete materials for reinforced concrete structures promotes the resistance and permeability of chloride penetration. Chloride penetration can deteriorate the durability of reinforced concrete structures before design life. Chang et al [3] examined that maximum chloride ingress occurred under wet-dry cycles. When chloride penetrates to concrete, it decreases the pH level. If chloride centration exceeds threshold, it can cause de-passivation of rebar by forming hydrogen chloride. As a result, rebars lead to corrosion and can cause concrete cracking and spalling. When concrete is cracked, it accelerates aggressive chemical penetration to concrete and can impact structural durability.

$$Fe + 2HCl \longrightarrow FeCl2 + H2 \quad (1)$$

Xu et al [7] studied chloride penetration effect of P.II 52.5 Portland cement by submerging into 0.5%, 2%, 3.5% and 5% concentration of sodium chloride solutions. All the specimens were kept wet for 6 days and dry for 1 day by controlling the room temperature. All the specimens were repeated this process for 12 weeks. Fig. 3 describes that when concrete is exposed to wet and dry cycles, chloride ions didn't penetrate as a straightforward pattern. Penetrate concentration decreased with depth. The deeper the depth, the less the chloride concentration. A peak chloride concentration occurred beneath the surface of the concrete. During wetting phase, chloride ions moved deeper into the concrete surface due to the capillary suction. On the other hand, chloride ions were redistributed during drying. Over time, this peak of chloride concentration moved deeper into the concrete. Chloride diffusion into concrete was higher under wet and dry conditions compared to normal environmental conditions.

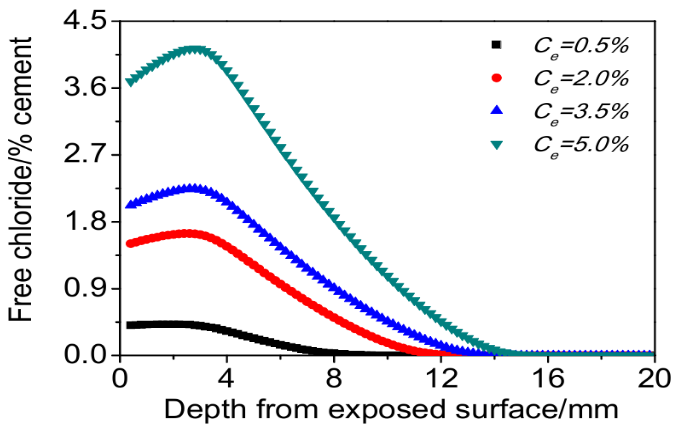

Fig. 3 Chloride distribution of concrete under various % NaCl concentration [7]

3. Methodology

3.1 Material mixed proportion

Within the scope of this research, 3D printed concrete and traditional concrete were performed to examine the durability performance especially on chloride penetration. Both concrete mixtures were designed to ensure as shown in Table 1.

Table 1 Mix proportion of 3DPC and normal concrete

Material components	Unit	3DPC	Normal concrete
Hydraulic Cement	kg/m^3	1,582	1,582
Fine aggregates	kg/m^3	98	98
Water	kg/m^3	440	440
Admixtures	kg/m^3	0.132	0.132
Density	kg/m^3	2300	2300
W/C ratio	kg/m^3	0.28	0.28
Compressive strength	MPa	≥50	≥50
Flow table test	mm	155-170	155-170
Setting Time	min	≥90	≥90

3.2 Sample size determination

3DPC and traditional concrete samples were prepared according to the desired mixed proportion as described in Fig. 4. Each type was tested by setting 28 ages of specimens. For normal concrete specimens, 15 cm x 15 cm x 15 cm cube specimens were used that was intended compressive strength more than 50 MPa.

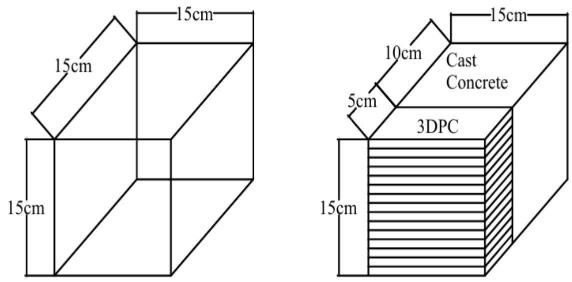

Fig. 4 Dimension of Normal Concrete and 3DPC

For the 3DPC specimens, the total length of the formwork was 15 cm. The width of each layer was 5 cm, and the thickness 1 cm. Total 15 layers were printed out that had 15 cm depth. After printing out 3D concrete layers, all the specimens were kept at room temperature for 7 days. According to previous research, the best bonding performance between 3DPC and post cast provided at the age of 7days. At the desired age, cast concrete was poured inside the prepared mold as shown inf Fig 6. All the testing specimens were prepared as illustrated in Table 2.

Fig. 5 3D Printed Concrete formwork

Fig. 6 3D Printed Concrete and Cast Concrete

Table 2 Number of Prepared specimens

Type of concrete specimen	Compressive Test	Chloride Penetration Depth
3DPC	-	3
Normal	3	3

3.3 Chemical curing process

For both 3DPC and Normal concrete, curing process were proceed by setting 28 days. All the testing specimens were kept at a temperature between 15°C and 30°C during the first 24 hours by protecting direct sunlight and extreme weather conditions according to the ASTM C31 standards and guidelines. In this research, a chemical curing process was carried out by spraying chemical curing agent to control proper hydration, strength, shrinkage and durability on the surface of the concrete as an external curing process in Fig. 7. After applying chemical curing agent both types of concrete, it was very important not to disturb the samples for 24 hours to form a protective layer.

Fig. 7 Spraying Sika to concrete surface

As a next progress the specimens were kept for 28 days by covering with plastic sheet. To check the concrete compressive strength, 3 specimens were taken.

3.4 Applying epoxy to specimens

In this research, using 3DPC as permanent was intended to be applicable in the actual situation. At the age of 27 days, five surfaces of both concrete specimens were coated with silicone. Only one surface of normal specimens and the extrusion surface of 3DPC was exposed to sodium chloride solution to satisfy with reality condition. After applying the coating, all the specimens were allowed to dry by the room temperature for 1 day.

Fig. 8 Applying Epoxy to the concrete surfaces

3.5 Submerging in sodium chloride solution

A sodium chloride solution with a concentration of 3% was prepared. All the sodium chloride was dissolved in water by using tank by regarding the water level. At the targeted date, specimens were immersed for 1 day into the solution as seen in Fig. 9. After that, the specimens were removed and allowed them to dry for 1 days. This wet-dry cycles were repeated up to 15 cycles. Chloride Penetration depth in the motor and 3DPC as permanent formwork was measured by preparing 0.1M silver nitrate solution. The average of 10 measurement points were taken and the chloride penetration depth were recorded. At the completed cycles, all the samples were split and sprayed the Silver Nitrate Solution.

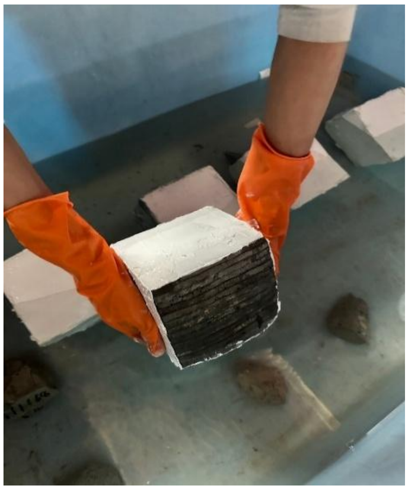

Fig. 9 Submerging testing specimens in NaCl Solution

4. Results and Discussion

4.1 Compression test

Compression testing was conducted according to ASTM C 39 standard. Three samples were taken from testing specimens. The compressive strength was 90 MPa.

Fig. 10 Compressive strength test of Cubic Specimen

4.2 Chloride penetration depth

After completing targeted cycles of specimens, they were split by using compressive machine. After split, the concrete surface was sprayed by using silver nitrate solution as shown in Fig. 11, waited for a few minutes and measured the chloride concentration depth into concrete by using clipper. Fig. 12 illustrated that the chloride effected area changed to white color while chloride free area remained brownish.

Fig. 11 Spraying Silver Nitrate Solution

Fig. 12 Chloride penetration depth for wet-dry 15 cycles

The chloride penetration depth of 3DPC is significantly higher than normal concrete. After completing 15 cycles of wet-dry condition, the maximum chloride penetration depth is 4 mm and 8 mm for normal concrete and 3DPC, respectively. Fig 13 shows the comparison of chloride penetration depth between normal and 3DPC. It is due to the additive manufacturing process of 3D printing process. As it is a layer-by-layer decomposition process creates a more porous structure than the solid material. The formation of porous structure allows and creates pathways to penetrate contaminants like chloride and carbonation.

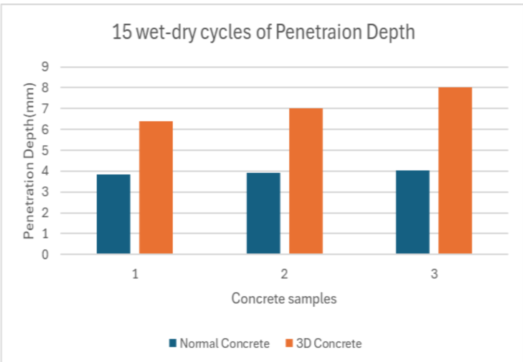

Fig. 13 Comparison of Normal Concrete and 3D Printed Concrete

While layers deposition, there is also a significant time gap between each layer. It also leads to enhance the porosity and permeability of chloride into concrete because of the gap and weaker bonds between layers during the printing process. Layer extrusion process on 3D printing technology also provides anisotropic microstructures. This means that the durability of 3D printed concrete can vary on the exposure direction. 3D printed technology is formwork less system and there is no such good water retention like traditional formwork system. As a result, it leads to more shrinkage and formation of voids in the 3D printing technology that reduces the overall durability of the material.

5. Conclusion

This study investigates the durability of 3DPC as permanent formwork for the extreme environmental conditions such as industrial areas and marine environment. The main objective of this research is to evaluate the chloride penetration depth under wet-dry conditions between normal and 3DPC as permanent formwork system, and the following conclusion can be withdrawn

(1) Normal concrete is less than 2 times chloride penetration of 3DPC because of its solid structure

(2) Chloride penetration is higher on 3D printed concrete due to its layer-by-layer extrusion process that can enhance the formation of porosity

(3) Using 3DPC as permanent formwork for reinforced concrete structures can also perform as load bearing elements

(4) 3DPC as permanent formwork can also enhance longevity and durability from external contaminants penetration like chloride and carbonation than traditional concrete with traditional formwork system

6. Acknowledgement

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