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CYCLE 1

FINAL REPORT

2023–2024

USDOT BIL Regional UTC
Region 6

Durability Assessment of Binders with Interlayer Reinforcement for 3D Printed Elements

Southern Plains
Transportation Center

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16. Abstract
Lack of knowledge and data about durability of 3D printed reinforced concrete structures hinders the growth of this digital fabrication method to truly offer its advantages towards civil infrastructure. 3D printed elements with Fiber reinforced polymers (FRP) reinforcement in successive layers may show increased resistance to deterioration mechanisms than typical steel reinforcement while improving flexural strength. This project investigates the effect of deterioration mechanisms such as chloride ingress and freeze and thaw on the mechanical performance, and flexural strength capacities of cementitious binders with FRP reinforcement in successive layers representing 3D printed elements. The information and knowledge achieved from this project can inform efficient solutions that help enhance the durability and resilience of elements constructed through digital fabrication methods like 3D printing.

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DURABILITY ASSESSMENT OF BINDERS WITH INTERLAYER REINFORCEMENT FOR 3D PRINTED ELEMENTS

FINAL REPORT
SPTC Project Number: CY1-OU-03

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List of Abbreviations and Acronyms

FRP............................Fiber Reinforced Polymer
DOT .... Department of Transportation
FHWA .... Federal Highway Administration
3DPC...........................3-D Printed Concrete
CFRP ....Carbon Fiber Reinforced Polymer
GFRP ....Glass Fiber Reinforced Polymer

Executive Summary

Bridges, tunnels, culverts, and various structural elements form the foundation of a nation's infrastructure. To maintain public safety and enable efficient transportation throughout the United States, the U.S. Department of Transportation (USDOT) prioritizes the design, construction, maintenance, and repair of these systems. Reinforced concrete, known for its strength and versatility, has become a standard material in many applications. With advancements in technology, innovative methods like 3D printing are revolutionizing the production of reinforced concrete components, significantly enhancing efficiency and scalability.

In this study, the hypothesis that environmental elements may negatively affect the flexural strength and interlayer strength of the concrete elements and the reinforcement at the interfaces are considered and durability assessment of cementitious binders with multiple interlayer reinforcement is performed to create high-quality 3D printed concrete (3DPC) elements for transportation systems. For that, the scope of this research covers the 3DPC and manually fabricated concrete with the reinforcements: carbon-fiber reinforced polymer (CFRP), glass-fiber reinforced polymer (GFRP) and steel reinforcement, to provide a comparative database for these advanced materials as reinforcements, as well as some additional benchmarks for the 3DPC. The environmental deterioration mechanisms-specifically: chemical ingress and freeze-thaw cycles are thoroughly studied including effects on the flexural and interlayer bond strength of 3DPC elements. By exploring the response of freeze- thaw conditions, and the chemical ingress, the effect of this harsh condition phenomenon can be better understood, and the necessary steps that can be taken to improve 3DPC for a durable and lasting infrastructure. Moreover, it is also anticipated that reinforcement like fiber reinforced polymers (FRP) will demonstrate better resistance to these deterioration mechanisms compared to traditional steel reinforcement, thereby improving the overall durability of 3D printed elements. However, given that the project has not been completed, the findings related to the mix design chosen, and the setting time obtained played a vital role in fabricating cubes and beams for the compressive strength and flexural strength as the project vital outcome. Also, the trend of crack propagation on the flexural beams also provided the preliminary idea on how the different types of reinforcement used are performing after being subjected to harsh conditions.

The selected concrete mix design performed exceptionally well, exhibiting a flow of just 1%. This limited flow ensures that the material remains stationary until pressure is applied by the 3D printer's pump. Due to this extremely low flow rate, the mix stays in place without spilling, allowing the printed structure to maintain its integrity. The mix had a setting time of 140 minutes, which is highly desirable for 3D printing as it provides ample time to complete the printing process and clean the equipment efficiently. The 28-day compressive strength was recorded at 80 ± 1.5 MPa, which was adequate for the fabricated beams. At 14 days, the compressive strength reached approximately 67 MPa—about 13 MPa lower than the 28-day strength. Consequently, extending the curing period to 28 days was deemed unnecessary, and the 14-day strength was chosen for practicality. Flexural strength tests conducted on specimens with no exposure showed cracks propagating vertically from top to bottom, indicating a robust bond. However, beams subjected to freeze-thaw cycles and chemical ingress exhibited significant deterioration. It is expected that failure will occur at the interface where the reinforcement is exposed, allowing ingress to penetrate and compromise the structural integrity. Since the interface is more vulnerable to environmental deterioration, it is recommended to use some protective coating using a polymeric resin on the interface which creates an impenetrable barrier system against the aggressive ions.

1 Introduction

Bridges, tunnels, culverts and different structural components form the basic backbone of any country's infrastructure. To ensure public safety and efficient transportation across the United States, the U.S. Department of Transportation (USDOT) emphasizes the importance of designing, constructing, retaining, keeping, and repairing these system. Because of its strength and flexibility, reinforced concrete is the benchmark material in numerous applications. Given the development of high-end technologies, techniques, which include 3-D printing, are emerging as a game changer for production of reinforced concrete components (Shahrubudin et al., 2019). 3-D printing, also known as additive manufacturing, has gained tremendous interest due to its ability to simplify processes, reduce material wastage and provide swift working that traditional methods simply cannot achieve. Similarly, in the context of transportation, 3-D printing offers opportunities for quicker construction and better cost efficiency, among other advantages. 3-D printing has a variety of branches, which could be the Fused Filament Fabrication (FFF), Selective Laser Sintering (SLS), Concrete 3-D printing, etc. but compared to its counterparts, the real-world applications of 3-D printing in reinforced concrete are still in its early stages typically considering the long-term durability aspects (Gebler et al., 2014; Shahrubudin et al., 2019).

A new technology might offer some extremely helpful benefits to mankind, but it comes with its own set of challenges. Despite its truly promising applications, the adoption of 3-D printed concrete (3DPC) for large-scale applications remains hindered through several vital demanding situations. One of the primary limitations includes inherently low tensile capacity and ductility. This affects its structural applications as conventional reinforcement cannot be used to withstand tension in the concrete. Another issue is that due to layer-by-layer stacking, the interface is extremely weak. Hence, for a 3DPC a strong interfacial bond is a prerequisite for strength and durability (Marchment et al., 2019). Now, due to the weak interfacial bond, layer's stiffness, time gap between the successive layer deposition, etc. play a vital role in determining the behavior of the structure (Roussel & Cussigh, 2008). The printed layers are extremely vulnerable to environmental deterioration which include chemical ingress, freeze-thaw cycles, and carbonation which can severely impact performance in the long run. Printed layer can reduce 50% of interlayer strength when it is left to dry in the environment (Marchment et al., 2019; Tay et al., 2019). In contrast to that, Austin et al. (Austin et al., 1995) reported that bond strength increases when the 3DPC is exposed to dry conditions, which implies that there exists a huge ambiguity as the conditions and parameters can vary each time for each mix and print.

The scope of this research addresses the 3DPC and manually fabricated concrete with the reinforcements: carbon-fiber reinforced polymer (CFRP), glass-fiber reinforced polymer (GFRP) and steel reinforcement, to provide a comparative database for these advanced materials as reinforcements and some additional benchmarks for the 3DPC. For that, the environmental deterioration mechanisms-specifically, chemical ingress and freeze-thaw cycles are thoroughly studied including effects on the flexural and interlayer bond strength of 3DPC elements. With this study, the necessary steps to improve 3DPC are recommended for a durable and lasting infrastructure. Moreover, it is also anticipated that reinforcement like fiber reinforced polymers (FRP), will demonstrate better resistance to these deterioration mechanisms compared to traditional steel reinforcement, thereby improving the overall durability of 3D printed elements. However, given that the project is not completed yet the findings like the mix design chosen, and the setting time obtained played a vital role in fabricating cubes and beams for the compressive strength and flexural strength as the main project outcome. Also, the trend of crack propagation on the flexural beams gave us the preliminary idea on how the different types of reinforcement used are performing after being subjected to harsh conditions.

1.1 Hypothesis

In this study, the following hypotheses will be tested:

i. Layer-on-layer compaction free 3D Printed elements have cold joints between layers and create an interface which may facilitate penetration of aggressive environmental elements.
ii. Environmental elements may negatively affect the flexural strength and interlayer strength of the concrete elements and the reinforcement at the interfaces.
iii. 3D printed elements with composite reinforcement, specifically FRP, may show increased resistance to deterioration mechanisms than steel reinforcement while improving flexural strength and interlayer shear capacities.

1.2 Objective

All main objectives of this study are listed below:

i. Assessment of durability properties of cementitious binders with multiple interlayer reinforcement to aid the deterioration caused by aggressive environment and development of high ductility 3D printed concrete elements for transportation systems.
ii. Preparation of comparison data sheet between the cementitious binders with successive layers representing 3D printed elements and reinforced cementitious binders with reinforcement incorporated at the interface between successive layers and providing microscopic analysis of failure surfaces.
iii. Suggesting the ideal reinforcement for the 3D printed elements from the data sheet.

1.3 Approach and Scope of work

In this study, the durability of 3DPC under the environmental degradation mechanisms of chemical ingress and freeze-thaw cycles was investigated in comparison with manually fabricated concrete with the flowchart in Figure 1. The approach concentrates on material selection, fabrication for both manual and 3D printed elements, durability assessment, microscopic analysis of surfaces and preparation of comparison data sheet.

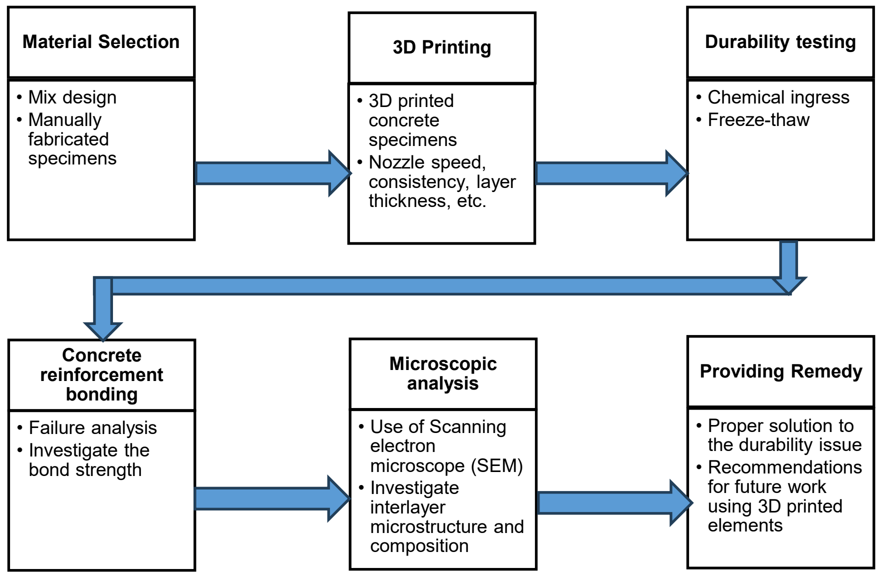


Figure 1: Approach of work

The scope of the work covers all the aspects of the experimental procedure like fabrication of 3D printed specimens and their long-term performance under given environmental exposure. Also, modifications on the mix design for minimizing the chemical ingress and boost the freeze-thaw resistance of the concrete. The work shall be a benchmark for applications of a 3D printer for large-scale printed elements in transportation such as bridges, culverts, etc. and should work as a guideline for using 3DPC in actual world considering all the environmental aspects.

2 Literature Review

2.1 3D Printed Concrete

3D Concrete Printing has emerged as a revolutionary innovation in the construction industry and has become a game changer for the way structures are planned and constructed. Without the use of formwork, the technology allows cementitious materials to be deposited layer by layer creating a stack of concrete layers which ultimately reduces the construction time and increases the material as well as the design flexibility (Nerella et al., 2019). Various technological approaches within this rapidly growing field have been presented and discussed in the literature. De Schutter et al. (De Schutter et al., 2018) and Bos et al. (Bos et al., 2016) addressed the potential challenges and provided some wide opportunities in this 3D printing field. Primary research has suggested that the 3D printer and 3D printed concrete can help cope up with the labor shortages and reduces the wastage of materials by significant amount (Buswell et al., 2018; Wangler et al., 2017). Rheological properties and strength of 3DPC have been a key point of attention in present day research (Buswell et al., 2018; Paul et al., 2018; Shahrubudin et al., 2019; C. Zhang et al., 2021). Moreover, it can be seen that a good control of hydration and setting kinetics of cementitious materials is crucial to meeting complex technological requirements like pumpability, extrudability, and buildability of fresh and hardened states need to be investigated (De Schutter et al., 2018; Perrot et al., 2016).

3DPC has pros that can outweigh the cons by a significant amount, the durability and reinforcement integration with 3D printed concrete is always a matter of deep concern and a tedious task but some innovative solutions have been suggested to reinforce the 3DPC. Strain-Hardening Cement- based Composites (SHCC) used as a 3D printed mix actually has higher strength compared to mold-cast SHCC specimens (Ogura et al., 2018). Another method named as Material Deposition Method (MDM) used a metal cable in the concrete to reinforce the printed concrete, which is very unique, and data shows that reinforcing could be possible in 3D printed mix as well (Bos et al., 2017). Similarly, this study dictates the use of steel as reinforcement is not feasible and suggests the use of using short fibers, yarns and textiles as reinforcement (Mechtcherine & Nerella, 2018). Traditional reinforcement methods, such as steel bars, are challenging to implement with 3D printed concrete due to the absence of formworks and its nature of stacking of layers on top of each other. Moreover, the durability of 3DPC where the layers are exposed to aggressive environments like chemical ingress, freeze-thaw and carbonation, etc. needs thorough investigation (El Inaty et al., 2023).

2.2 Layer-by-layer intrusion

The layer -by-layer construction technique in 3D printer is unique and at the same time a very challenging thing for all the engineers and experts unlike conventional concrete. The concrete printing or 3D printing process uses an additive, layer-based, manufacturing technique to build complex geometrical shapes without the need of formworks, thus has a unique advantage over conventional construction methods. This is performed with contour crafting, which is based upon layer-by-layer extrusion of a cement-based paste creating a smooth surface through buildup of subsequent layers (Le et al., 2012). In extrusion-based 3DPC, the requirements of structures fabrication are both good flowability and a layer should be able to support the weights of subsequent layers, i.e. the printed concrete needs to have a unique shear strength, material properties like: thixotropy and viscosity (Nishiwaki et al., 2021; Zhang et al., 2023). Apart from this, investigation on the effect of stacked layers vertically on the printed elements is also equally important because due to the soft nature of freshly prepared concrete without formwork can have different deformations in the successive layers, to support the upper layers. Hence, the adhesion can vary with each layer. Stacking layers vertically causes higher bond strength in the middle interfaces than upper and lower interfaces according to Yu Zhang.et.al (Zhang et al., 2023).

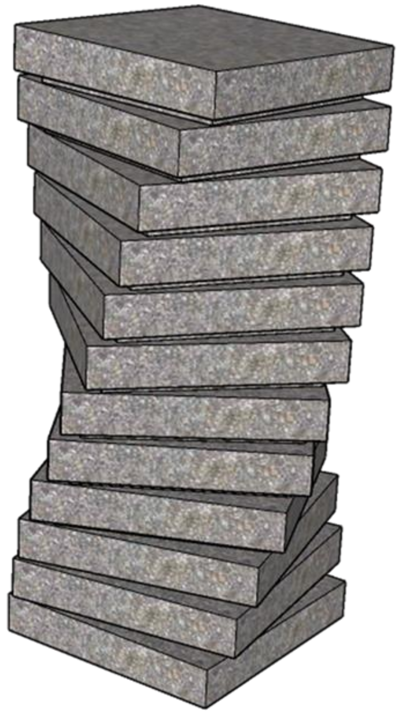


Figure 2: Layer-by-layer stacking sequence

2.3 Freeze-thaw on 3D Printed Concrete

Freeze-thaw is one of the most severe environmental degradation factors affecting concrete durability. When water penetrates through the concrete pores and freezes inside the concrete, it expands and causes degradation of mechanical properties. Cyclic freezing and thawing causes excessive damage and decreases the lifespan of the structure. For conventional concrete air-entraining admixtures are used but for the 3DPC it is not possible due to lack of formworks and exposed layer-by-layer stacking which possesses significant risk to freeze-thaw deteriorations (Fagerlund, 1977; Guo et al., 2022). Experimental investigations for freeze-thaw for 3DPC are still in early stages and laboratory tests have shown that proper mix design can cope properly with the freezing and thawing cycles. Even some studies suggested that glass fibers can improve the freeze-thaw resistance by resisting the crack propagation and hence achieve extended ductility before rupture (Wang et al., 2022; Warsi et al., 2023).

To study freeze-thaw mechanisms, a freeze-thaw chamber which can vary in shapes and size needs to follow ASTM 666 for freezing and thawing mechanisms guidelines (ASTM International, 2024b). The freeze-thaw chamber freeze phase occurs at -18°C (0°F), and the thawing at 4°C (40°F). The phases of the freeze-thaw cycle are outlined in Figure 3. Specimens are removed every 30 ± 6 cycles. However, the study on freeze-thaw on 3DPC is extremely limited and this study aims to provide the necessary benchmark regarding the freeze-thaw resistance on 3DPC.

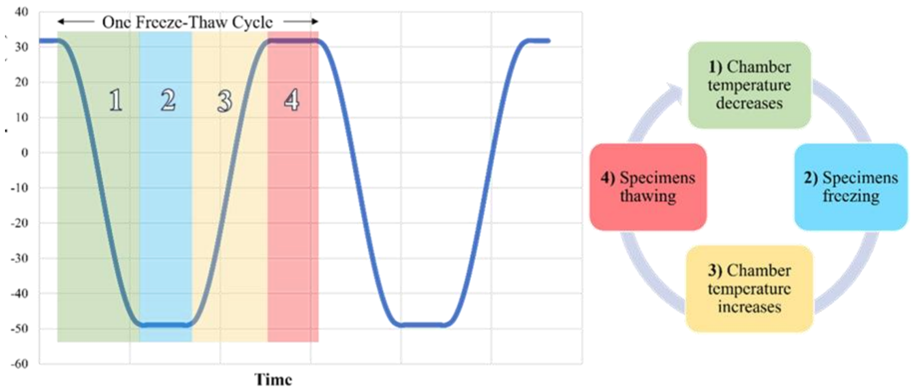


Figure 3: Freeze-thaw cycles process

2.4 Chemical Ingress on 3DPC

Chemical ingress, which includes chloride, sulfates and carbonation is one of the leading causes of durability issues in concrete. The ingress could severely affect the concrete from decreasing its lifespan to huge extent to corrosion, expansion-cracking and decrease in mechanical properties which are overall considered environmental degradation factors. In 3DPC, the layer-by-layer deposition process introduces additional vulnerabilities at the interfaces where the chemical can percolate inside and can accelerate the ingress (Siddika et al., 2020; Y. Zhang et al., 2021). Chloride ingress is a major concern for reinforced concrete typically for concrete in marine conditions. Studies have shown that 3DPC are more susceptible to chloride penetration due to the gaps on layer-by-layer stacking of 3D printed concrete layers (Van Der Putten et al., 2020).

Similarly, carbonation is where carbon dioxide from the atmosphere reacts with calcium hydroxide to form calcium carbonate in the cement paste which ultimately deteriorates the concrete (Malan et al., 2021). Moreover, sulfates are also equally responsible for the chemical ingress in 3DPC. Sulfate attack occurs when the surrounding environment reacts with cement causing extensive cracks and loss in concrete's capacity. The layer acts as an easy entry point for the sulfate ions for getting inside the 3DPC (Baz et al., 2021). Despite the significant surge in research for the chemical ingress in 3DPC, significant progress has been made where Van Der Putten. et Al. (Van Der Putten et al., 2020) gave some significant results on chloride penetration, however, the ingress refers to sulfate as well which is still lagging in the current study. Most of the studies are confined to small-scale specimens, with limited time ingress, which is not relevant to the real-world conditions. Hence, this study tries to fill this gap and works as an initiator for more research on ingressive environment on 3DPC.

3 Materials and Methodologies

3.1 Mix Design

The mix design for 3DPC plays a vital role in assuring proper printability, ability to gain proper tensile and overall structural performance. An ideal mix design should possess a proper printability possessing a rheological profile that allows smooth extrusion without segregation or clogging. Also, the printed mix should be able to retain the shape while providing proper stacking sequence with proper bond between the adjacent layers. The mix should be durable enough to restrain the ingress of chemicals through it. Chlorides, sulfates and carbon dioxide are highly permeable compounds which tend to attack and ultimately deteriorate the mix. Also, the mix should be able to support the weight of the top layers. Incorporating additives like fibers and reinforcement can contribute to the ductility and tensile capacity. The mix design was carefully curated through research from literature, running multiple trial and error for both the strength and workability requirements, analyzing particle size distribution for fine aggregates. The water/binder ratio of mix design for the study is 0.28. The constituents of the study are:

Table 1: Components of mix design

Material	Quantity
Cement	546 kg/m^3
Fly Ash	156 kg/m^3
Silica Fume	78 kg/m^3
Sand	1171 kg/m^3
Water	219 kg/m^3
High-range water reducer (HRWR)	8.2 kg/m^3

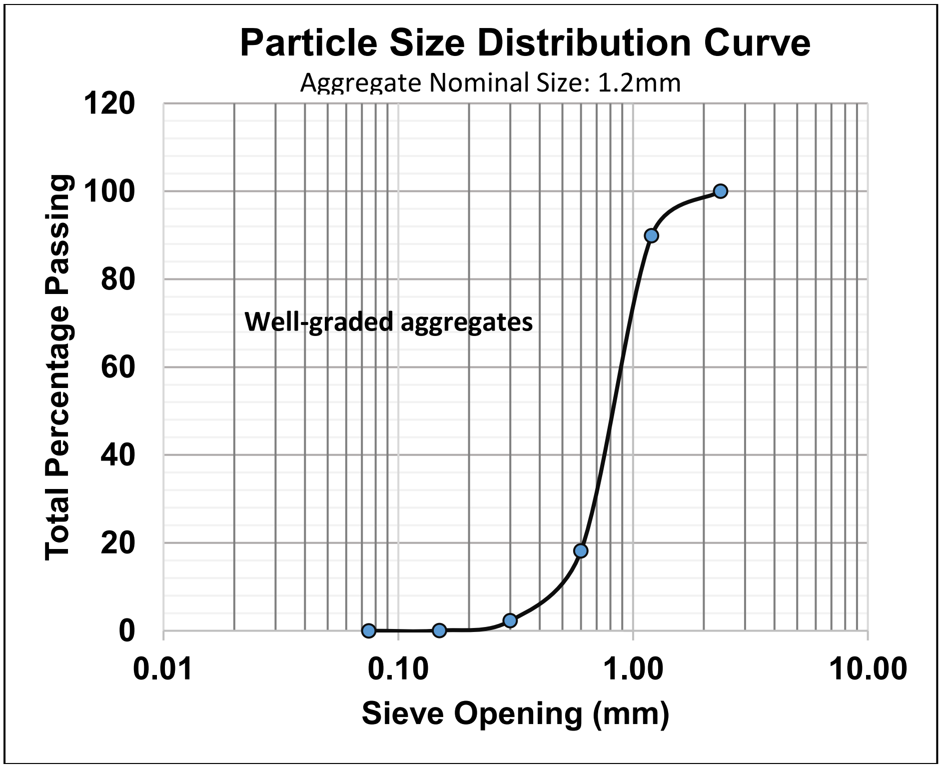


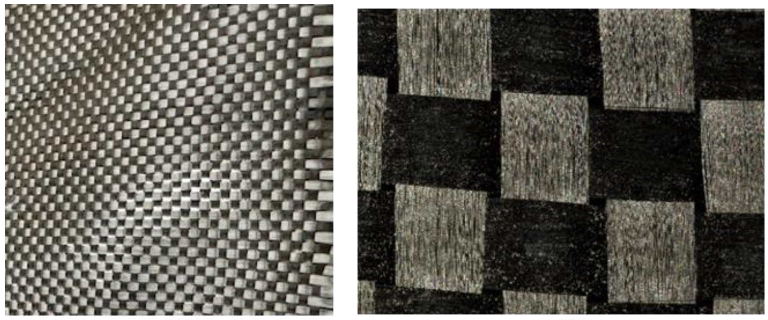
Figure 4: Particle size distribution curve for fine aggregates

3.2 Reinforcements

The reinforcement plays a significant role in enhancing the performance of the mix. It helps assisting the tensile strength, ductility, addressing the brittle nature of the concrete. For the 3DPC the placement of reinforcement is a very tedious task, particularly on the interface where weaker bond can create deterioration. The reinforcements used in this study are:

3.2.1 Carbon Fiber-Reinforced Polymer (CFRP)

The CFRP fabric is made up of carbon fiber which is embedded in a polymer matrix. The CFRP fabric offers high strength to weight ratio, corrosion resistance, is extremely lightweight and highly durable. The CFRP Fabric in Figure 5 is more popular in the current context due to its wide range of applications in reinforcing the 3DPC. Which ultimately offers a very strong alternative to traditional steel reinforcement.

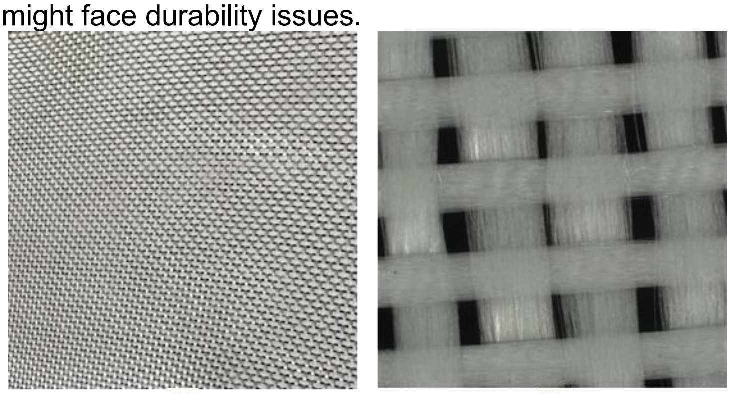


(a) (b)

Figure 5: (a) CFRP Fabric (b) Microscopic 40X image for CFRP Fabric

3.2.2 Glass Fiber-Reinforced Polymer (GFRP)

The GFRP fabric is made up of glass fibers which are properly embedded in a polymer matrix, that can offer an economical and extreme resistance to corrosion. It has wide applicability due to its lightweight and cost-efficient nature. In 3DPC, GFRP fabric in Figure 6 is a perfectly suited candidate for reinforcement in aggressive environments where traditional steel reinforcement might face durability issues.



(a) (b)

Figure 6: (a) GFRP Fabric (b) Microscopic 40X image for GFRP Fabric

3.2.3 Steel Reinforcement

Steel mesh is a conventional reinforcement technique composed of interconnected steel wires or bars, forming a grid-like pattern. The wide range application of steel in construction is due to its high tensile strength, availability, and cost-effectiveness. In this study the 3DPC steel mesh in Figure 7 is introduced to prepare a comparable dataset and to know how the environmental degradation affects the actual concrete and steel that is used.

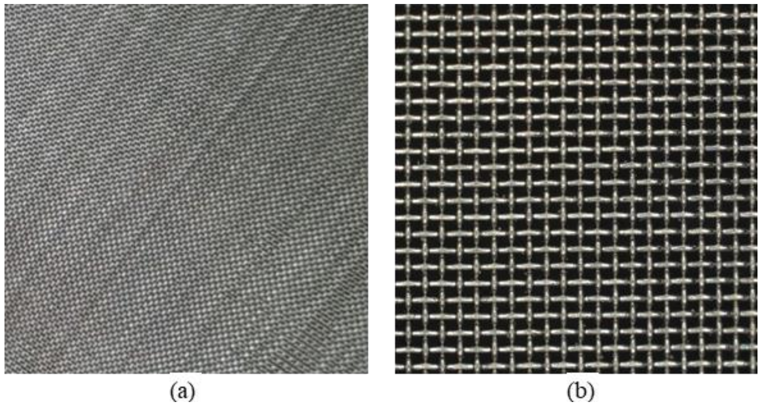


Figure 7: (a) Steel Mesh (b) Microscopic 40X image for Steel Mesh

Microscopic analysis of each type of reinforcement is performed to investigate the gap sizes in the fibers for CFRP, GFRP and steel reinforcement. For that, Keyence VHX-7000 ultramicroscope at the Samuel Roberts Noble Microscopy Lab (SRMNL) at the University of Oklahoma was used to obtain the images in Figure 8 just making sure that the materials that are to be compared should be of similar shape and size to make them more like an apple-to-apple comparison.

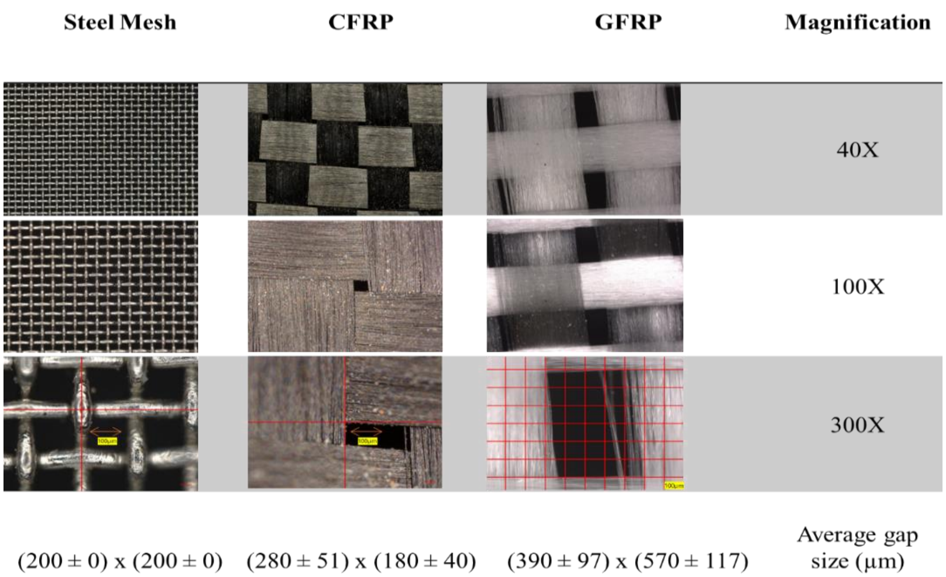


Figure 8: Microscopic images of reinforcement used along with fibers gap size

3.3 Flow and Setting time

Flow or standard test method for flow of hydraulic cement mortar (ASTM C1437) is a standard test method used to determine the workability or consistency of the mix that does not have coarse aggregates. It evaluates the flow by assessing how the mix spreads on the flow table.

This test is useful for quality control and ensuring the mix meets the desired specifications for applications (ASTM International, 2020). Specific procedures include the mold which is filled in two layers followed by 20 tamps each and then the table is dropped 25 times under 15 seconds and then mold is removed. The mix properly flowed into the table and hence, the flow of the mix is measured. The flow table is shown in Figure 9.

Figure 9: Flow table

Setting time or Standard test methods for time of setting of hydraulic cement by Vicat Needle (ASTM C191-18a) is a standard test method used to determine the time of setting of hydraulic cement. This test measures the rate at which cement starts to set which is very crucial for workability and construction timing. Specific standard procedures involve filling the mold for Vicat’s apparatus and a 1mm diameter needle is lowered and the penetration is recorded every 15 minutes. The Vicat’s apparatus is shown in Figure 10. Final set time is achieved when the needle does not make any penetration and leaves a mark on the surface (ASTM International, 2019).

Figure 10: Vicat's Setting time apparatus

3.4 Preparation of specimens for compressive strength test method

The standard test method for compressive strength of hydraulic cement mortars using 2-in. or 50-mm cube specimens is to determine the compressive strength of hydraulic cement mortars. The test is critical for evaluating the strength properties of cementitious materials used in construction and is often used as a benchmark for material performance. Standard procedures include cubes of molds 50mm x 50mm where mix is placed in two layers of compaction 16 times each as shown in Figure 11. The cubes are demolded after 24 hours and are cured for 7, 14 and 28 days respectively (ASTM International, 2024a).

Figure 11: 50mm x 50mm cementitious cube preparation

3.5 Compressive Strength test

The cementitious cubes that are cured for 7, 14 or 28 days are placed on Forney compression testing machine and load is applied until failure. The ramp rate used is: 0.206 MPa/sec and the preload applied is 1.112 kN as shown in Figure 12

$$\text{Compressive Strength} = \frac{\text{Maximum Load (N)}}{\text{Cross-Sectional Area (mm}^2\text{)}}$$

Figure 12: Forney compression testing for cubes

3.6 Fabrication of specimens by manual fabrication

Manually fabricated specimens of dimensions 4-in x 4-in x 15-in were cast and the reinforcement is placed 1-in from top and bottom faces as shown in Figure 13. The beam size used was fixed according to the freeze-thaw and chemical ingress chamber's area restrictions.

(a) (b)

Figure 13: (a) Reinforcement placement (b) 4-in x 4-in x 15-in manually fabricated specimens

3.7 Preliminary Flexural Strength test

Manually fabricated 28 days cured beam specimens were tested on Forney compression testing machine using a 4-point bending test with ramp rate of 0.0173 MPa/sec and preload of 2.224 kN. A load is applied until the specimens failed in flexure as shown in Figure 14. The flexural testing was performed to check whether the bond between the concrete and the reinforcement is strong enough or not. The rest of the flexural testing is to be performed on 250 kN MTS 810 hydraulic frame using LVDT sensors at displacement 1mm/min which shall provide the necessary deflection data following ASTM C580 and ASTM C78.

(a) (b)

Figure 14: (a) Forney flexural testing setup (b) 4-point bending test setup

3.8 Specimen Deterioration

3.8.1 Chemical Ingress

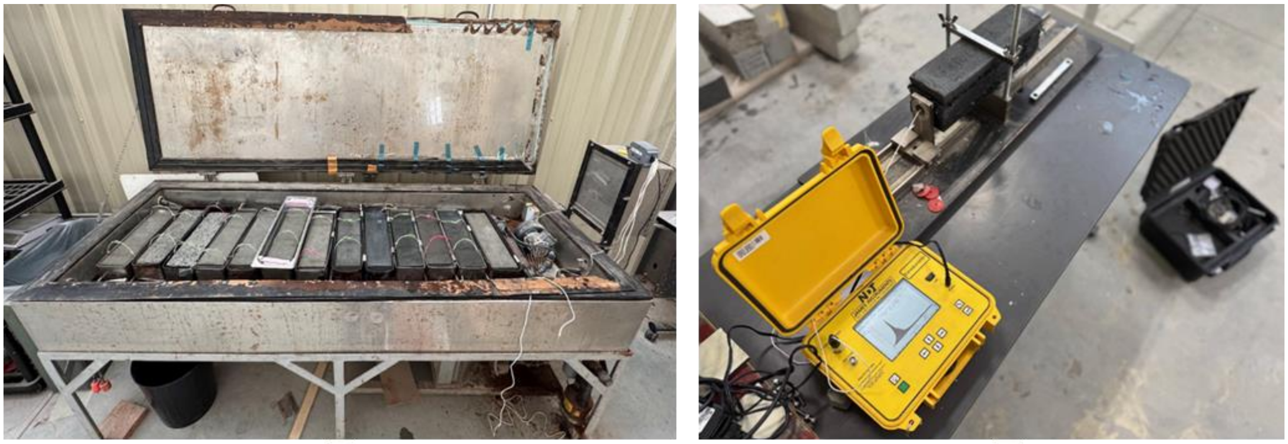
A chemical ingress chamber is created with water and 6% NaCl solution. Sulfuric acid is added regularly to maintain a pH less than or equal to 2 as shown in Figure 15. After that the 14 days cured beam specimens are placed in the chamber and ingress is measured at 30 days interval.

(a) (b)

Figure 15: (a) Chemical ingress chamber (b) pH of chamber maintained less than 2

3.8.2 Freeze-thaw

The 14-day cured beam specimens were placed in a freeze-thaw chamber (ASTM 666)(ASTM International, 2024b). Frequency and dynamic modulus of elasticity are directly correlated. Over the cycles the dynamic modulus of elasticity decreases as the cracks reduce the concrete's ability to resist deformation hence the stiffness decreases, the material becomes less elastic and more brittle, leading to a drop in resonant frequency. The chamber is shown in Figure 16. Specimens are removed and testing for dynamic modulus every 30 ± 6 cycles. The test is stopped when the relative dynamic modulus of elasticity at given cycle 'n' is obtained when frequency at 'n' cycles is 60-70% of its initial value. To measure the frequency, accelerometers measure the vibrational response of concrete which is embedded in the device named emdoumeter.



(a) (b)

Figure 16: (a) Freeze-thaw chamber (b) Emdoumeter

4 Results and Discussions

4.1 Flow, Setting time, and Compressive Strength

The flow of the mix was less than 1% which seems to depict that the mix had almost zero flowability. Similarly, Vicat's initial setting time of the mix obtained was 140 minutes. This implies that the time for the printing and cleaning should be under 140 minutes. The 28 days compressive strength obtained for 2-in x 2-in, or 50-mm x 50-mm cubes was 80.0 ± 1.5 MPa. These materials and results are:

(a) (b) (c) (d)

Figure 17: (a) Vicat's needle (ASTM C191-18a) (b) Flow table test (c) Forney compression testing for 2-in x 2-in cubes (d) Failed cube specimen

Table 2: Compressive Strength data

Curing (days)	Compressive Strength (MPa)
7	59.4 ± 0.4
14	67.1 ± 0.1
28	80.0 ± 1.5

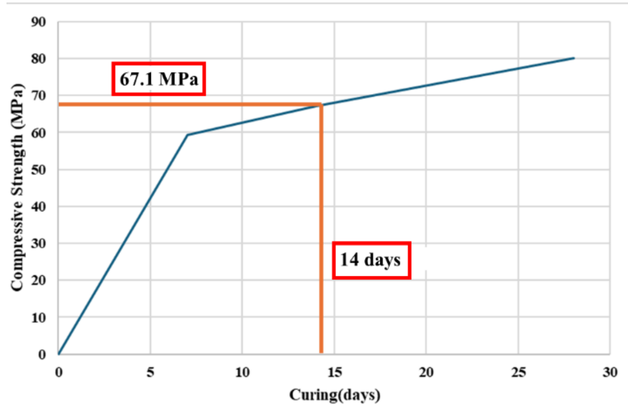


Figure 18: Compressive Strength vs Curing time

4.2 Preliminary Flexural Strength – 0-day exposure

One of each manually fabricated beam specimens having each type of reinforcement was tested in flexure after curing to understand the 0-day exposure conditions for flexural strength. Results showed that each type of reinforcement aided the integrity of the beam.

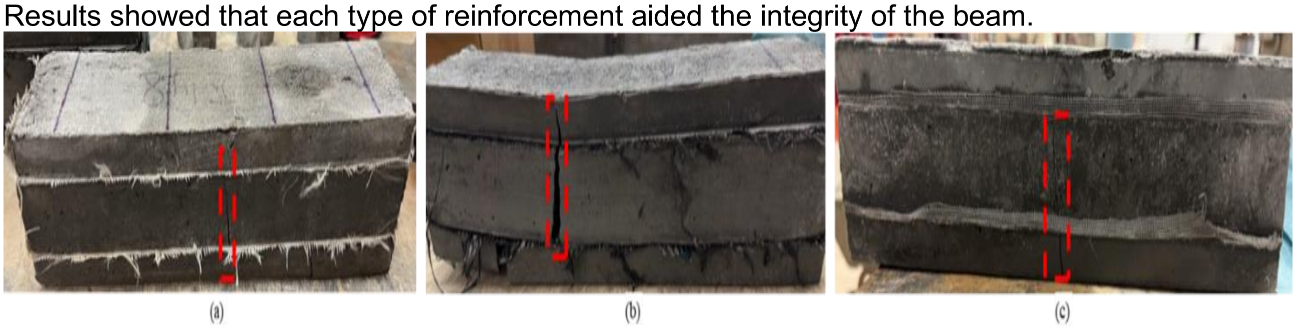


Figure 19: (a) 0-day exposed GFRP beam after failure (b) 0-day exposed CFRP beam after failure (c) 0-day exposed Steel beam after failure

The failure surface of GFRP and CFRP seems the crack is penetrating from top to all the way to the very bottom as shown in Figure 19, which implies that the bond between the concrete and the reinforcement is good and strong.

4.3 Deterioration Mechanisms

4.3.1 Chemical Ingress

Beam specimens are progressively getting deteriorated due to the chemical getting inside the specimens through the interface as seen in Figure 20. Similarly, bonding between the reinforcement and the concrete due to the chemical ingress is getting weaker each Figure 20. The deterioration was recorded after 74 days of ingress. Which is proven by the degradation of reinforcement on the external side and formation of cracks on the specimen which is getting larger each day.

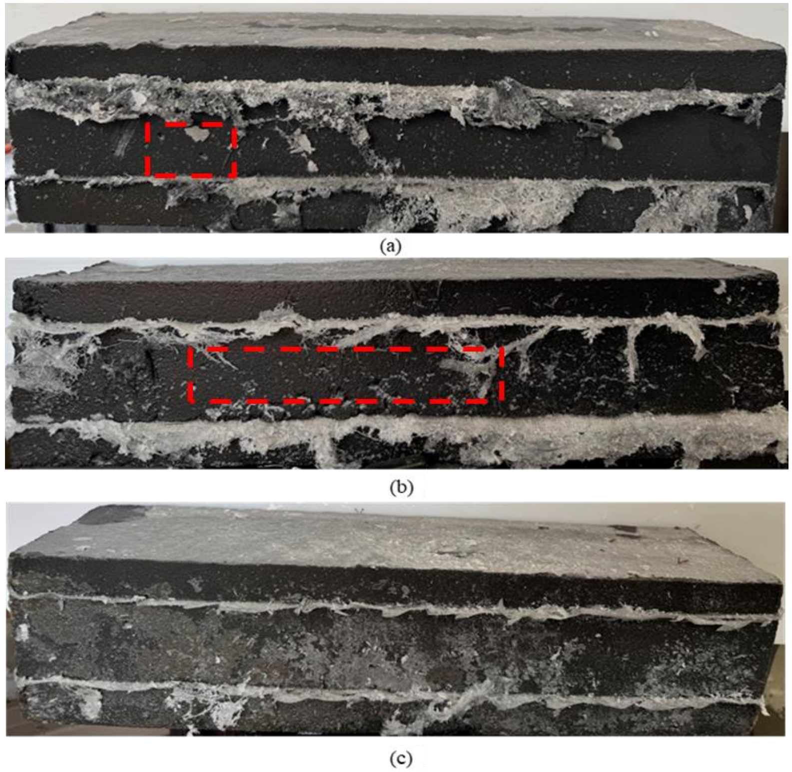


Figure 20: Beam deterioration due to chemical ingress after 74 days (a) CFRP (b) GFRP (c) Steel reinforcement

4.3.2 Freeze-thaw

Beam specimens are progressively getting deteriorated due to freeze-thaw cycles. Bonding between the reinforcement and the concrete due to freeze-thaw action is getting weak, which is followed by the cracks that could be seen on the surface and are getting wider with exposure time interval. The red rectangles show the deterioration of the specimens and cracks being developed. Freeze-thaw deterioration could also be determined from emdoumeter by plotting resonant frequency vs number of freeze-thaw cycles in Figure 22. It is an ongoing work so from 100 to 150 cycles, CFRP has shown a downward trend and again rose sharply afterwards. Steel has always been on top and rising. However, from 150 to 200 cycles, both CFRP and GFRP have shown rise in frequency. The specimens are intact after 221 cycles of freeze-thaw for CFRP and GFRP and 150 cycles for steel reinforcement.

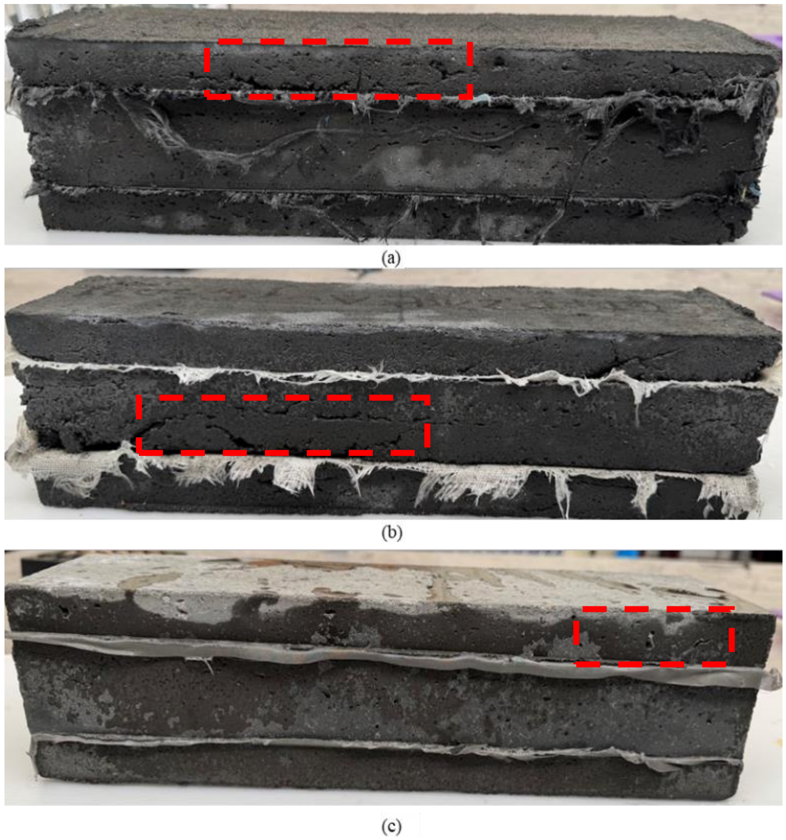


Figure 21: Beam deterioration at 221 freeze-thaw cycles for (a) CFRP (b) GFRP (c) 150 cycles for Steel reinforcement

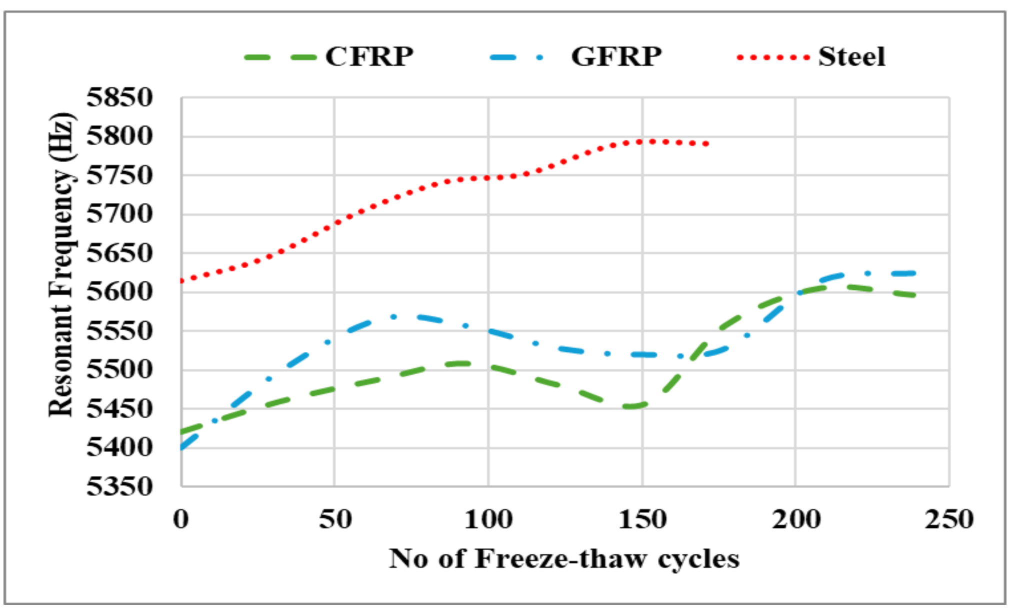


Figure 22: Resonant Frequency vs No of Freeze-thaw cycles

5 Ongoing and Future Work

5.1 Printing Specimens

Once the 3D printer is set up and operation checks are complete, the proposed mix design shall be used to fabricate the beam specimens of same size of 4-in x 4-in x 15-in as the 3D printed beam specimens. The Scara Elite Roadrunner 4M concrete 3D Printer shall be used with an extrusion pump which is necessary equipment for extruding the concrete out of the nozzle. The 3D printer is shown in the Figure 23. The step-by-step printing involves first mixing the concrete and making sure the concrete does not set quickly. The set time obtained was 140 minutes. Then powering on the 3D printer and the pump, making sure that the print is already programmed to the 3D printer. Then, turning the pump on and waiting for 3D printer to do its job.

Figure 23: Scara Elite Roadrunner 4M and Extrusion Pump

5.2 Flexural tests

When all the 3D printed and manually fabricated specimens are cured and aged in respective chemical ingress or freeze-thaw chamber, the specimens are taken out and placed under 250 kN MTS 810 hydraulic frame using LVDT sensors at displacement 1mm/min on mid span which shall provide the necessary deflection data with load following ASTM C580 and ASTM C78. The setup is shown below on Figure 24. Load is applied until the specimen's failure. Failure surfaces shall be thoroughly studied.

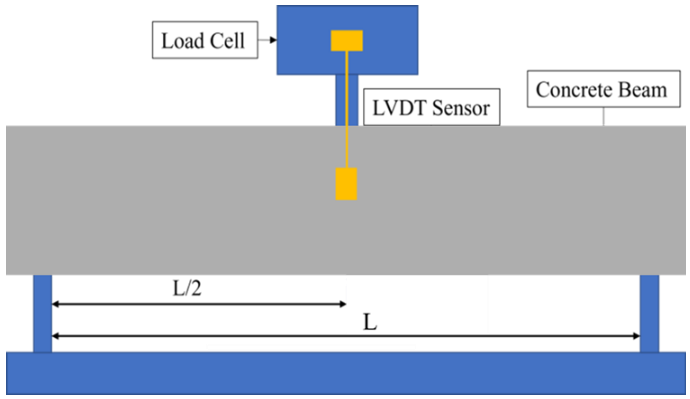


Figure 24: Flexural test setup on 250 kN MTS 810 hydraulic frame

5.3 Solutions

The study will provide solutions on how to minimize environmental deterioration affecting the 3DPC and investigate preventative measures. The major solutions that this study will investigate are listed below and shown the **Error! Reference source not found.** (Heras Murcia, 2 021; Murcia, 2021):

1. Methods to protect the 3DPC interfaces by polymer surface finishings by using a polymer resin on the interface which creates an impenetrable barrier system against the aggressive ions.
2. Investigate the effect of a printed protective barrier using the same 3D printed mix with sufficient design modification to create a strategic interface mismatch where interface can allow ingress but due to mismatch of outer protection system, ingress getting in is significantly reduced. On the other hand, the same 3D printed mix will ensure homogeneity and bond with printed systems.

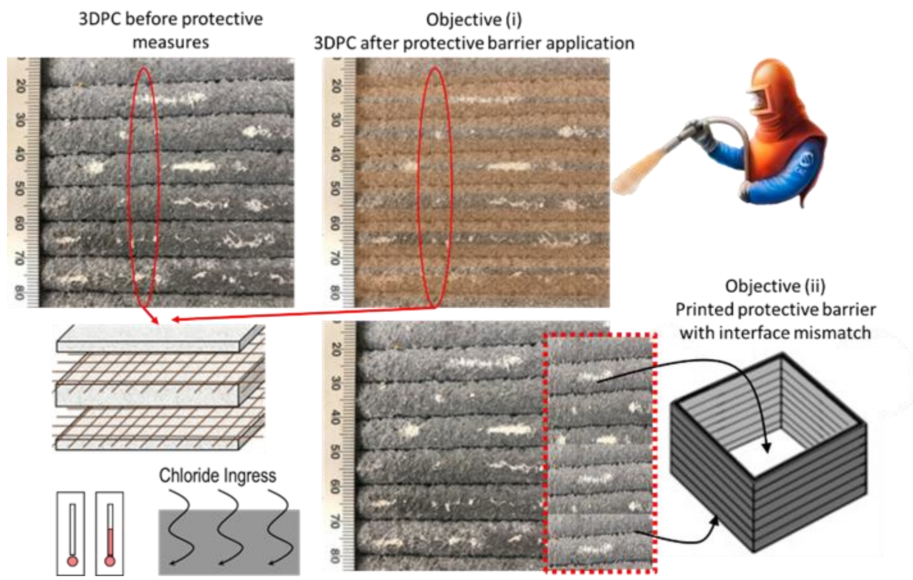


Figure 25: Schematic showing possible solutions

5.4 Microscopic analysis

The failed specimens from flexural tests are to be analyzed using light microscopy**-** The Keyence VHX-7000 ultramicroscope at the Samuel Roberts Noble Microscopy Laboratory on the University of Oklahoma campus is utilized to investigate the failure modes of flexural specimens. Each type of reinforcement used shall be different so failure mode, and crack propagation may be different due to varying conditions may differ, hence, microscopic validation of the failure interfaces focused on understanding reinforcement behavior, bond between binder and reinforcement and failure modes with exposed and un-protected vs exposed and protected interlayers will be performed on all tested specimens.

6 Conclusions and Recommendations

With the current progress of the project, it can be concluded that the mix design that was chosen for the concrete stood out very well having the flow of just 1% that means the flow is very limited until the pump of the 3D printer applies the pressure. And since the flow is extremely low, the mix placed in one place does not spill out and the printed structure shall remain intact. The setting time of the mix was 140 minutes, which is very high and desirable since the printing job requires a lot of time so the time obtained shall be more than enough to finish the job and clean the machines properly. Similarly, the 28 days compressive strength obtained was 80 ± 1.5 MPa which was sufficient strength for the beams that were fabricated. Given that the 14 days strength was around 67 MPa which is around 13 MPa less than the 28 days strength. Hence, an extra 14 days was avoided, and 14 days strength was chosen. Moreover, the flexural strength data for 0-day exposure showed the cracks propagating from top to bottom all the way that means the bond is very sturdy. For the freeze-thaw and chemical ingresses, beams are extremely deteriorated. It is anticipated that the failure shall be from the interface where the reinforcement is exposed so that the ingress can penetrate inside and cause damage to the structure.

Since the interface is more vulnerable to environmental deteriorations, it is recommended to use some protective coating using a polymeric resin on the interface which creates an impenetrable barrier system against the aggressive ions. Also, the investigation of a printed protective barrier using the same 3D printed mix with sufficient design modification to create a strategic interface mismatch where interface can allow ingress but due to mismatch of outer protection system, ingress getting in might be significantly reduced.

7 Implementation of Project Outputs

The project output addresses the use and printing of the specimens using the 3D printer which is up and running currently. Before having to run the print thoroughly, proper calibration for the 3D printer is mandatory and is running, just to make the final work as refined as possible. Specimens are placed on chemical ingress tube and freeze-thaw chamber where some deteriorations can be seen on the surface. Hence, the comparison of the exposed vs non-exposed beams can be achieved eventually. Soon the 3D printed specimens shall be printed out and the same exposure conditions shall be applied for those ones as well broadening our scope of comparison.

8 Technology Transfer and Community Engagement and Participation (CEP) Activities

1. The team has hosted 25 middle school students from Lexington Public school in Fears lab to educate on the benefits and design flexibility with 3D printing technologies. The students were thrilled to experience concrete reinforcement materials and had an opportunity to visualize the strength of concrete through an ASTM standard test.

Figure 26: Lexington School students observing 3D printed polymers

Figure 27: Lexington School students observing concrete 3D printer

Figure 28: Lexington School students observing cube compression test

2. The PI along with Dr. Robert Nairn as Co-PI have submitted a Workforce development proposal: 3D-Printing Experience for Undergraduates. 3D-Printing Experience for Undergraduates is a 10-week program to help support 5 to 6 undergraduate students who are involved, or wish to become involved, in training and research in 3D printing and development. In the pilot study, UG students from OU will be invited to participate in the application process developed by the investigators in coordination with Jeff Cooper. The methodology of this pilot program will include using the 3D printing equipment described below. Students will explore and propose designs that are under compression similar to a biomimicry approach that require geometric flexibility to support structural characteristics, its internal environment, ventilation characteristics and application that traditional manufacturing methods do not enable.

9 Invention Disclosures and Patents, Publications, Presentations, Reports, Project Website, and Social Media Listings

(1) the following reports have been submitted

- January, April, July and October quarterly reports to Southern Plain Transportation Center (SPTC) submitted

(2) the following conference posters and presentation have been delivered

- Poster presentation on Transportation Industry and Workforce Development Symposium - April 30, 2024, University of Oklahoma, Norman, OK
- Poster presentation on 2024 Summer Transportation Symposium – July 30, 2024, OSU Hamm Institute, Oklahoma City, OK
- Poster presentation on Graduate Student Poster Fair & Networking Event, Sept. 26, 2024, University of Oklahoma, Norman, OK
- Poster presentation on Oklahoma Transportation Research Day (OTRD), Oct. 15, 2024, Grand Ballroom, University of Central Oklahoma, Edmond, OK
- Presentation on ACI Concrete Convention, Fall 2024 for ACI-440D Committee, Marriot Downtown, Philadelphia, PA
- Poster presentation on Advanced Materials, Nov. 15, 2024, West Atrium, Sarkeys's Energy Center, University of Oklahoma, Norman, OK

(3) the following journal paper was submitted:

Adhikari, S., Akbarpour, A., Volz, J., Floyd, RW., Vemuganti, S., Thermoplastic Carbon Fiber Reinforced Polymer Tapes in Cementitious and Polymer Concretes. Submitted for review to Functional Composites and Structures.

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