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Influence Of Nano-Coated Micro Steel Fibers On Mechanical And Self-Healing Properties Of 3d Printable Concrete Using Graphene Oxide And Polyvinyl Alcohol

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ABSTRACT

High Ductility Cementitious Composites (HDCCs) are emerging as suitable materials for 3D concrete printing due to their superior tensile strength and crack resistance. These composites typically contain a high volume of micro steel fibers to improve ductility and structural integrity. However, excessive fiber content negatively impacts the fresh properties of the concrete, increases porosity, reduces durability, and significantly raises production costs. To overcome these challenges, this study introduces a novel nano- coating technique where graphene oxide (GO) is applied to micro steel fibers using polyvinyl alcohol (PVA) as a binder. This coating improves the bond between the fibers and the cement matrix, enabling better stress distribution and crack control. As a result, the required fiber dosage can be reduced without compromising mechanical performance. Mechanical tests such as compressive strength, direct tensile strength, and flexural tests were conducted to assess the modified composite. Additionally, self-healing behavior was examined by pre-loading samples and allowing a healing period. The results indicate that nano-coated fibers not only enhance strength characteristics but also promote autogenous self-healing, making the material more durable and cost-efficient for advanced 3D concrete printing applications.

Keywords: 3D Concrete Printing; Nano-Coated Micro Steel Fibers; Graphene Oxide; Polyvinyl Alcohol (PVA); Self-Healing Concrete; Sustainable Construction; Advanced Construction Technology; Indian Construction Industry.

1. INTRODUCTION

1.1. 3DCP: ADVANCES AND CHALLENGES

In recent years, 3D Concrete Printing (3DCP) has emerged as a revolutionary construction method due to its potential to reduce labor, speed up construction, and create complex geometries. A commonly used material for 3DCP is Ultra- High Ductility Concrete (UHDC), which is known for its excellent mechanical performance and crack resistance. UHDC typically includes silica sand, supplementary cementitious materials (SCMs), and a high volume of fibers— often ranging from 1% to 2% by volume—such as steel, basalt, or polyethylene (PE) fibers. While these fibers improve strength and ductility, their high dosage negatively impacts the fresh properties of the concrete. It reduces workability, complicates the extrusion process, and increases the need for superplasticizers. Additionally, the cost of using such large quantities of fibers is a significant concern for large-scale or practical construction applications. Therefore, researchers are actively exploring alternative solutions to reduce fiber dosage while retaining the desired mechanical properties of UHDC.

1.2. GO NANOTECH FOR FIBER REINFORCEMENT

One promising direction is the incorporation of nanomaterials, particularly graphene oxide (GO), to enhance the performance of cementitious composites. Nanomaterials, due to their high surface area and unique chemical properties, can improve hydration, reduce porosity, and strengthen the interfacial transition zone (ITZ) between the fibers and the cement matrix. Researchers have found that coating fibers with nanomaterials can significantly enhance their bond with the surrounding concrete, increase resistance to crack initiation and propagation, and improve pull-out strength. Despite several studies exploring nano-coatings using materials like nano-silica, carbon nanotubes, and nano- calcium carbonate, there has been limited focus on applying graphene oxide coatings to micro steel fibers, particularly in the context of 3D printable concrete. Additionally, the self- healing capacity of such nano-coated fibers in concrete remains largely unexplored. Given the importance of crack repair and durability in structural applications, there is a critical need to investigate how GO-coated fibers can improve both strength and self-healing behavior.

1.3 EXPERIMENTAL STUDY WITH GO-COATED FIBERS

To address this gap, the current study proposes a novel and practical method of applying graphene oxide (GO) coatings on micro steel fibers using polyvinyl alcohol (PVA) powder as a coupling agent. This approach aims to simplify the coating process while effectively improving the interaction between the fibers and the cement matrix.

The research focuses on three key objectives: evaluating the impact of GO nano- coating on the mechanical properties of 3D printable concrete, analyzing crack width reduction at failure, and assessing the self-healing performance over time. A low dosage of GO (0.03% by cement weight) was used, based on previous studies, and different PVA concentrations were tested to identify the most effective coating method. The base concrete mix used was a reference 3DCP mixture from previous research, modified by incorporating 2% by volume of nano-coated micro steel fibers.

The experimental program involved mechanical testing—such as compressive strength, direct tension, and flexural tests—to evaluate the structural performance of the 3DCP mixtures. To assess self-healing, pre-cracking was done by loading the samples up to 80% of their ultimate capacity, followed by a healing period of 105 days under controlled wet-dry cycles. Crack closure was monitored for flexural samples, and strength recovery was measured through displacement-controlled reloading. The results showed that the GO-coated fibers significantly improved the mechanical strength of the printed concrete while also reducing the final crack widths.

More importantly, the coated fibers enhanced the self-healing ability of the concrete, as evidenced by better crack closure and strength recovery compared to uncoated fiber mixes. This indicates that nano-coating with GO using PVA as a coupling agent can serve as a cost-effective and efficient method for improving the durability and mechanical performance of 3D printable concrete, even at lower fiber dosages.

2. EXPERIMENTAL PROGRAM

2.1. MATERIALS AND MIXTURES

2.1.1. MATERIAL SELECTION AND MIX COMPOSITION

In this experimental program, Type II Portland cement with a density of 3.1 g/cm³ was used as the primary binder. The fine aggregate used was silica sand, selected due to its favorable properties for 3D printable concrete mixes. It had a water absorption capacity of 1.0%, a specific gravity of 2.68, a bulk density of 1500 kg/m³, a fineness modulus of 3.1, and a maximum particle size of 2.36 mm. For consistency across all mixtures, a fixed sand-to- cement ratio of 1.5 was maintained, which is standard for achieving good flowability and buildability in 3DCP applications. The reinforcing element in this study was a straight, copper-coated micro steel fiber with a diameter ranging from 0.20 to 0.25 mm, a length of 12–14 mm, and an ultra-high tensile strength of 2850 MPa. The fibers were added at a volume fraction of 0.75%. For nanomaterial enhancement, graphene oxide (GO) was used at a dosage of 0.03% by the weight of cement, based on optimal values found in previous studies. The GO used had a specific surface area of 40 m²/g, a high purity of 98.5%, an average flake thickness of 60 nm, and a lateral particle size of less than 7 µm. Given the sensitivity of GO to agglomeration, a meticulous dispersion protocol was adopted as previously developed by Mousavi and Dehestani, ensuring a uniform distribution in the cementitious matrix.

2.1.2. NANO-COATING PROCESS FOR STEEL FIBERS

A novel nano-coating technique was developed to apply the GO nanomaterials onto the surface of micro steel fibers using polyvinyl alcohol (PVA) powder as a coupling agent. PVA was chosen for its excellent binding properties and compatibility with both GO and steel fibers. It has a chemical formula of $(C_2H_4O)_n$, a density of 1.19 g/cm³, and an ignition temperature of 450°C. The nano-coating process involved seven critical steps. First, the micro steel fibers were thoroughly cleaned using 96% ethanol to remove any impurities or surface contaminants. Next, the cleaned fibers were oven-dried at 75°C. Simultaneously,PVA and GO were prepared in separate aqueous solutions.

Table 1. Physical properties of micro steel fibre.

Material	Diameter (mm)	Length (mm)	Tensile strength (MPa)
Low carbon steel	0.20–0.25	12–14	2850

Figure 1. Micro steel fibers used in the present study.

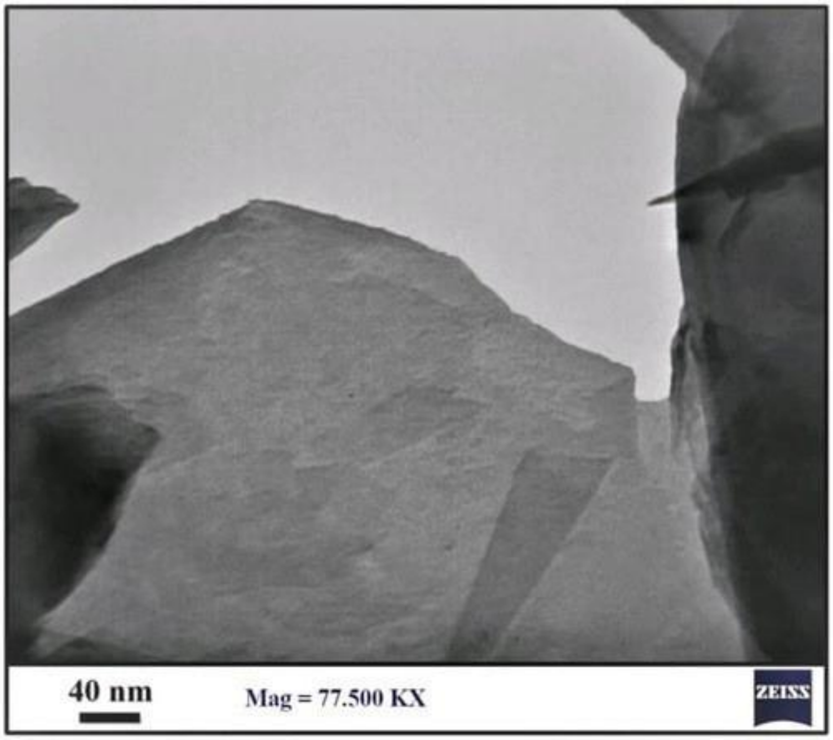


Figure 2. TEM Image of GO nanomaterials.

The PVA was dispersed by gradually heating water in a magnetic stirrer up to 90°C and maintaining this temperature for 4.5 hours at 700 rpm. After cooling to room temperature, the GO was dispersed in deionized water using a combination of magnetic stirring and ultrasonic probing—10 minutes of stirring followed by 30 minutes of ultrasonication. These two solutions (PVA and GO) were then mixed and stirred together for an additional 15 minutes. The final solution was poured into a flat container containing the pre-dried steel fibers, which was then placed in an oven at 75°C for 24 hours to complete the coating process. The result was a batch of uniformly GO-coated steel fibers ready for use in 3D printable concrete mixtures.

2.1.3. MIXTURE DESIGN AND SPECIMEN PREPARATION

The study evaluated five different 3DCP mixtures, all prepared with a constant water-to-cement (W/C) ratio of 0.42, selected based on earlier research validating its compatibility with extrusion-based printing. The variable factor in the mixtures was the nano-coating technique applied to the steel fibers, classified into three types: A, B, and C. In Type A, a PVA-to-water ratio of 1:70 was used during the PVA dispersion phase. Type B involved a more concentrated PVA ratio of 1:23, enhancing the thickness and adhesion of the coating. Type C also used a 1:23 PVA ratio but introduced an additional step where the final PVA+GO solution underwent ultrasonication for 30 minutes to ensure homogeneous dispersion of nanomaterials.

Table 2. Mix proportions of 3DCP.

Mixes	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Micro Steel Fibers	
				Normal (% volume fraction)	Nano-coated (% volume fraction)
Ref	450	189	675	–	–
F	450	189	675	0.75%	–
CF1	450	189	675	–	0.75% Type A
CF2	450	189	675	–	0.75% Type B
CF3	450	189	675	–	0.75% Type C

The primary difference among these types was in the amount of coupling agent used and the specific dispersion method employed, while the GO dosage remained constant across all samples. These coated fibers were then incorporated into the 3D printable concrete mixtures. The fresh mixes were poured into molds and covered with plastic sheets for 24 hours to minimize moisture loss.

After demolding, all specimens were cured in a water tank at 20°C and 60% relative humidity for a standard 28-day period to allow full hydration and strength development.

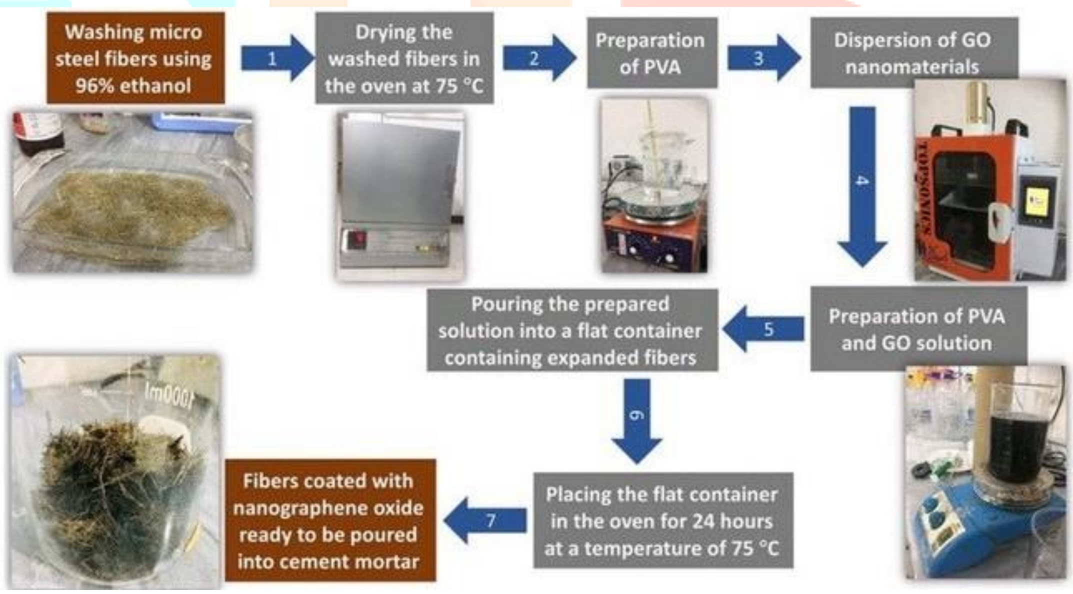
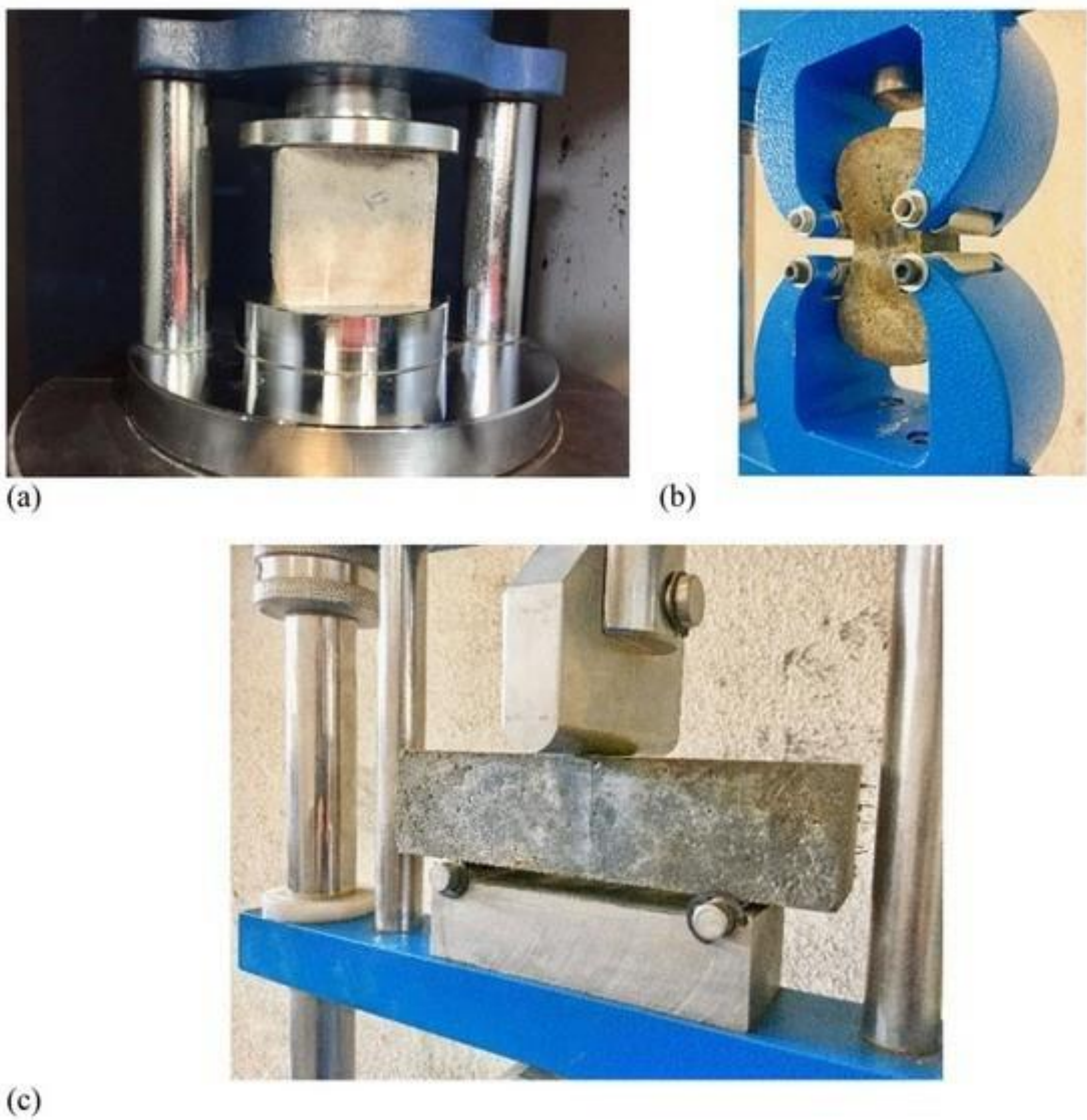


Figure 3. Coating methods used in the literature for fibers in cementitious composites.

Figure 4. Ultrasonic bath used in type C of nano-coated fibers.



2.2. EXPERIMENT TESTS

Three mechanical tests were considered for the experimental program, including concrete compressive test, direct tensile test, and flexural test (Figure 5). Regarding compressive strength, three 50 mm cubes were considered for each mixture (Figure 5(a)). To measure the tensile strength of 3DCP samples, briquette specimens were used based on AASHTO T 132 , ASTM C307 , and ASTM C190 . The bone-shaped tensile specimen had a length of 76.2 mm, a thickness of 25.4 mm, and a cross-section of 645 mm^2 at mid-length (Figure 5(b)).Three-point bending test was also performed after 28 days of curing within a 40×40×160 mm prism mold (Figure 5(c)). A constant displacement rate of 1.27 mm/min was considered for direct tensile and bending tests. Regarding self-healing measurement, both crack sealing and crack healing was measured in the present study.

Figure 5. Experimental tests considered in the present study: (a) compressive test for intact samples; (b) direct tensile test for intact samples; (c) bending test for intact samples; (d) bending tests for healed samples after pre- cracking.

Closure of cracks due to the generation of healing products (such as precipitation of calcium carbonate) is denoted as cracksealing, while strength regaining after healing periods is called crack-healing. Crack-sealing is essential for the durability properties of concrete specimens and can be appropriately achieved by considering precise healing periods.

However, it is worth mentioning that crack healing is a complicated phenomenon. Preloading (displacement-controlled) until 70% of maximum crack widths observed in the tensile and flexural tests was considered to simulate internal damages. The visualized examination was supposed to compare the crack width before and after the healing periods. Wet-dry cycles (more than three months) were considered a healing regime, followed by previous studies. One wet-dry cycle denotes 24 h in water followed by 24 h in dry conditions. To quantify the self- healing capacity of 3DCP mixtures, a healing improvement factor (IF) was used, which is defined by Eq. (1):

$$IF = \left[\frac{F_{Healed} - F_{precracked}}{F_{Uncracked} - F_{precracked}}\right] \times 100 \qquad (1)$$

It is worth mentioning that Eq. (1) demonstrates the crack-healing capacity (or strength regaining), which was similarly used by the literature.

3. RESULTS

3.1. MECHANICAL CHARACTERISTICS

3.1.1. COMPRESSIVE STRENGTH PERFORMANCE

The compressive strength results demonstrated a positive influence of micro steel fibers and nano-coating techniques on the mechanical performance of 3D printable concrete. The control mixture incorporating 0.75% uncoated micro steel fibers (designated as mixture F) exhibited a 17.7% increase in compressive strength compared to the plain mix without fibers. Further enhancements were

(a)

(b)

Figure 6. Failure of compressive samples: (a) before test; (b) after test.

observed with the application of nano-coated fibers. Specifically, mixture CF1, utilizing a type A nano-coating, achieved a 14.2% increase in compressive strength relative to mixture F. Mixture CF3, incorporating type C nano-coating with ultrasonic dispersion, showed a 2.5% improvement over F.

The enhanced performance of CF1 is attributed to the optimized polyvinyl alcohol (PVA) to water ratio in the initial coating solution, which resulted in better fiber coverage and improved interfacial bonding. In contrast, mixture CF2 (type B nano- coating), which used a higher PVA content than water, exhibited a 2.5% reduction in compressive strength relative to F. This reduction is likely due to excessive polymer deposition, leading to inadequate dispersion and poor bonding. The inclusion of ultrasonic treatment in CF3 compensated for this effect, leading to a 5.1% improvement over CF2. These findings underscore the significance of both

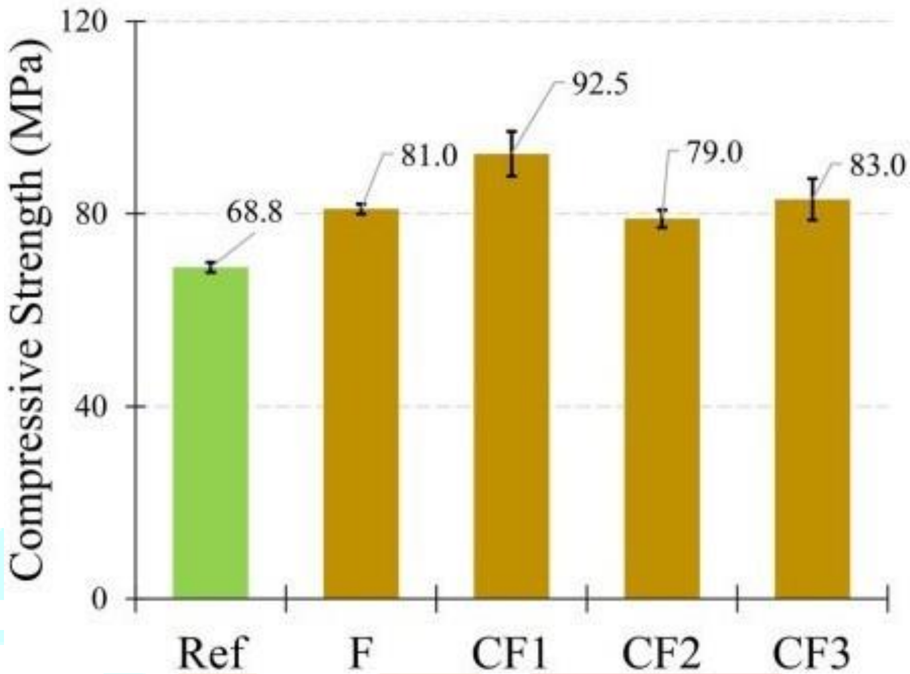


Figure 7. Results of the compressive strength test.

coupling agent concentration and dispersing methodology in nano-coating applications. No variation in failure modes was observed among the compressive test specimens, as shown in Figure 7.

3.1.2. DIRECT TENSILE STRENGTH PERFORMANCE

Direct tensile strength tests further confirmed the beneficial effects of fiber reinforcement and nano-coating. The uncoated fiber mix (F) demonstrated an 83.3% increase in tensile strength compared to the fiberless reference mix (Ref). Enhanced tensile strength was also observed in mixtures containing nano- coated fibers. Mixtures CF1, CF2, and CF3 showed tensile strength improvements of 21.2%, 6.1%, and 15.2%, respectively, over F.

Figure 8. Failure of direct tension samples.

Among the nano-coated samples, CF1 exhibited the highest tensile strength. This is attributed to its optimized type A nano-coating, which led to reduced interfacial porosity and improved fiber-matrix adhesion. The presence of graphene oxide (GO) in the coating system played a crucial role in performance enhancement. The wrinkled surface texture and two- dimensional structure of GO platelets contributed to improved mechanical interlocking at the interface. Additionally, functional groups present on GO, such as carboxylic acids, formed covalent bonds with hydration products (C– S–H and $Ca(OH)_2$), enhancing the chemical bond strength.

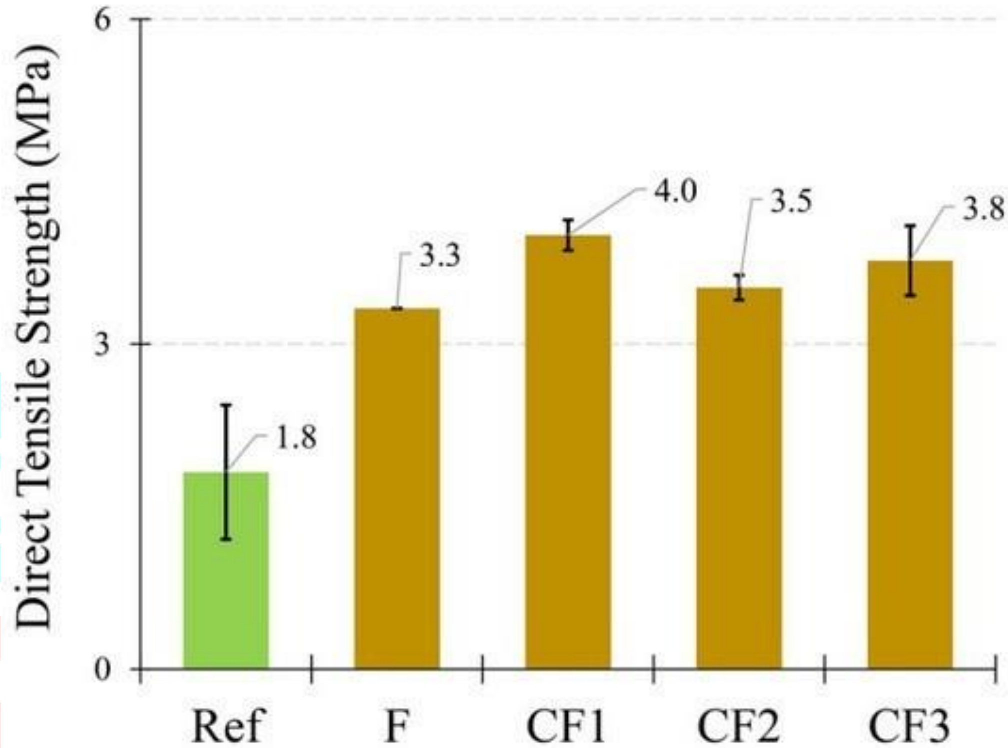


Figure 9. Results of direct tensile strength test.

The nano-coating process also increased the surface roughness of fibers and repaired surface flaws at the micro/nano-scale, further contributing to load transfer efficiency. Although CF2 showed reduced tensile strength due to suboptimal dispersion, the application of an ultrasonic bath in CF3 recovered much of the performance loss. Similar to the compressive strength test, all tensile samples failed in a similar mode, with no distinct differences observed (Figure 9).

3.1.3 FLEXURAL STRENGTH AND CRACK WIDTH CONTROL

Flexural strength measurements indicated that nano-coating did not significantly compromise load-carrying capacity. Mixture CF1 demonstrated comparable or slightly improved flexural strength relative to the uncoated fiber mix (F). Mixtures CF2 and CF3 showed minor reductions in flexural strength—4.9% and 10.4%, respectively—indicating that the coating type and process influence the structural behavior under bending.

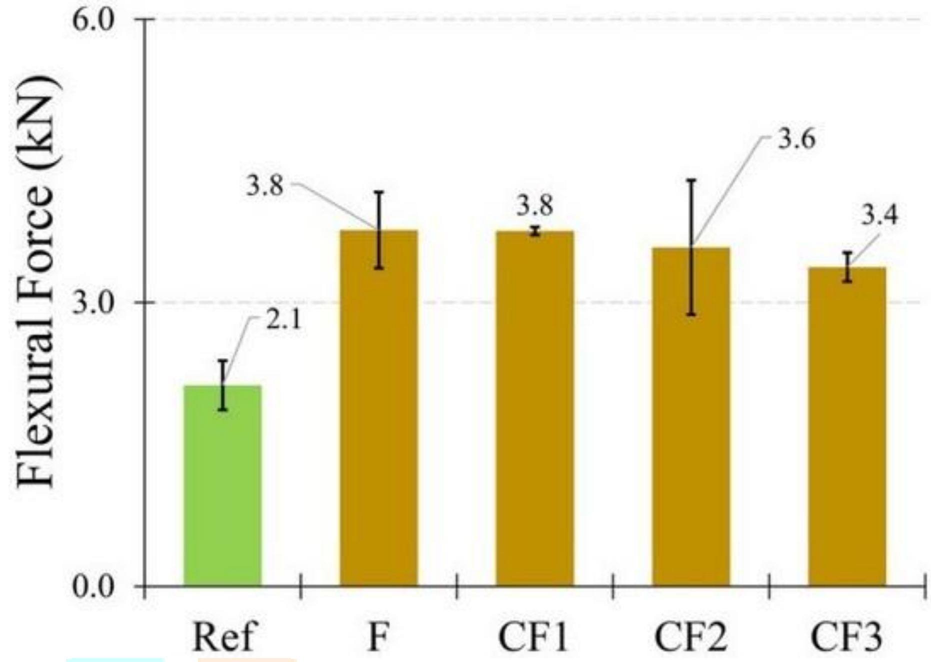


Figure 10. Results of the flexural test.

In contrast to flexural strength, notable improvements were observed in crack width control. Mixtures CF1, CF2, and CF3 exhibited crack width reductions of 73.7%, 26.3%, and 36.8%, respectively, relative to F (Figure 12). The superior performance of CF1 is linked to the effectiveness of the type A nano-coating in promoting strong interfacial bonding and enabling an efficient fiber-bridging mechanism. The inclusion of GO nanomaterials enhanced the fiber-matrix interface and contributed to better crack arrest capabilities.

Additionally, the use of ultrasonic dispersion in CF3 led to a more uniform fiber coating and reduced variability in crack width measurements when compared to CF2. High standard deviations in crack width were observed across all samples, consistent with the known brittle behavior of concrete.

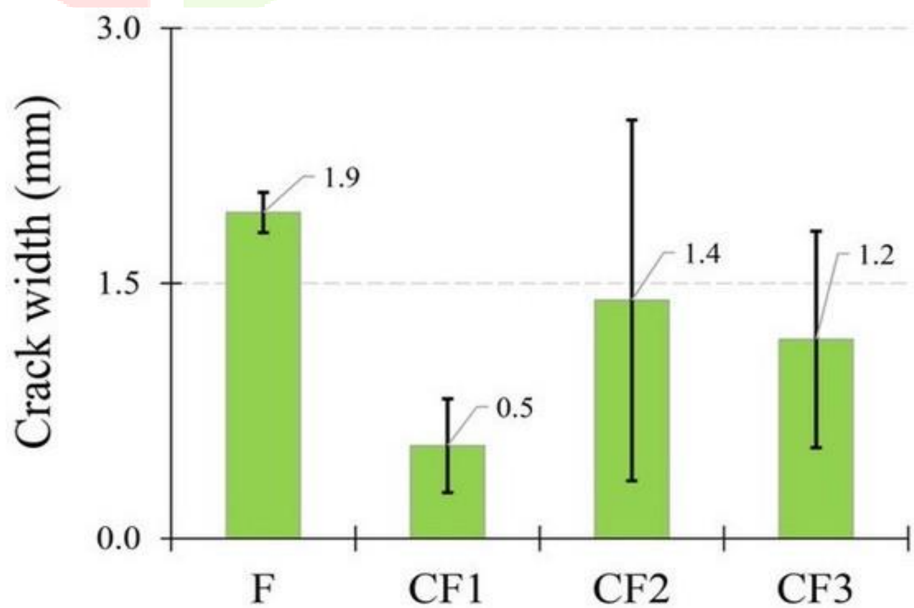


Figure 11. Crack width of flexural samples at failure.

Figure 12. Failure of flexural samples: (a) mixture of 'F'; (b) mixture of 'CF1'; (c) mixture of 'CF2'; (d) mixture of 'CF3'.

These findings highlight the critical role of coating formulation and process parameters in enhancing flexural performance and crack control in 3D printable concrete.

3.2. SELF-HEALING PROPERTIES

3.2.1. VISUAL AND MECHANICAL EVALUATION OF SELF-HEALING BEHAVIOR

Micro steel fibers enhance the self-healing behavior of concrete by (1) limiting crack propagation and (2) acting as nucleation sites for healing product formation at crack tips. In this study, graphene oxide (GO) nanomaterials were applied as a surface coating on steel fibers to further improve these mechanisms. The GO coating increases fiber surface roughness and promotes localized healing reactions at the fiber–matrix interface.

After 105 days of wet–dry cycling, visual evidence of healing was clearly observed in both tensile and flexural specimens. White crystalline deposits appeared at the crack outlets, consistent with findings in the literature that identify such formations—commonly referred to as "stalactites"—as calcium carbonate ($CaCO_3$) and other hydration products (Figures 13 and 14). The GO- coated fibers facilitated crack sealing through a self-cure mechanism based on their ability to absorb and retain moisture near the cracks, thereby sustaining hydration reactions.

In addition to visual crack sealing, the mechanical recovery of pre-cracked samples was evaluated. Post-healing strength tests showed notable strength regain in all mixtures containing nano-coated fibers. Healing improvement factors ranged from 7.9% to 34.3% in tensile specimens and from 10.3% to 43.9% in flexural specimens (Figure 15), confirming the potential of nano- coated fibers to support autogenous healing under cyclic environmental conditions.

3.2.2. INFLUENCE OF NANO-COATING PARAMETERS ON HEALING EFFICIENCY

Among the tested mixtures, CF2—utilizing the type B nano-coating technique —exhibited the highest healing efficiency, despite its relatively low initial mechanical strength.

This performance is attributed to the higher content of polyvinyl alcohol (PVA) in the initial dispersing solution used for fiber coating.The excess PVA likely retarded the early hydration process around the fiber surface, preserving a greater quantity of unhydrated cement particles in the matrix. During the healing period, these particles were reactivated through moisture ingress, contributing to strength recovery.

The presence of GO nanomaterials further accelerated this process. The functional groups on the GO sheets, such as carboxylic acids, react with cement hydration products like C–S–H and $Ca(OH)_2$, enhancing chemical bonding and promoting the formation of healing compounds. The increased surface area and roughness provided by the GO coating also supported physical adhesion of healing products, thereby improving the durability of the crack closure.

These findings highlight the importance of optimizing nano-coating parameters —such as PVA content and dispersion method—to balance initial mechanical strength and long-term healing efficiency. While CF1 achieved superior mechanical performance, CF2 showed superior self-healing capacity. Further experimental investigations are recommended to better understand the interaction between coating composition, curing conditions, and long-term performance of self-healing in 3D printable concrete systems.

4. CONCLUSION

4.1. EXPERIMENTAL OBJECTIVE AND METHODOLOGY

An experimental program was undertaken in the present study to investigate the effects of nano-coating micro steel fiber surfaces using graphene oxide (GO) nanomaterials and polyvinyl alcohol (PVA) powder on the mechanical and self- healing performance of 3D printable concrete. The core objective was to evaluate whether the incorporation of nano-coated fibers could allow for a reduction in fiber dosage without compromising structural performance. To this end, steel fibers were coated with GO using varying quantities of PVA as a coupling agent. Different dispersion methods were also applied to optimize coating uniformity and performance. The intent was to enhance interfacial bonding, improve load transfer across cracks, and evaluate the feasibility of producing more efficient and self-healing 3D printable cementitious composites.

Figure 13. Crack sealing in direct tension samples after the healing period.

4.2. INFLUENCE OF NANO-COATING ON MECHANICAL PROPERTIES

Based on the results of the mechanical testing, it was found that among the three nano-coating techniques studied, the optimized use of PVA in the GO dispersion led to the most reliable coating quality. Specifically, mixtures using an appropriate PVA concentration in the coating solution demonstrated mechanical performance enhancements of 14.2% in compressive strength and 21.2% in direct tensile strength compared to mixtures with uncoated fibers. These improvements are attributed to increased surface roughness, enhanced fiber– matrix interlocking, and the formation of chemical bonds between GO functional groups and cement hydration products. This finding supports the viability of nano-coating as a method to reduce the quantity of steel fibers required in printable concrete without sacrificing strength.

4.3. FLEXURAL BEHAVIOR AND CRACK WIDTH REDUCTION

In flexural strength testing, the performance of nano-coated fiber mixtures was found to be comparable to that of uncoated fiber mixtures in terms of load- bearing capacity. However, significant improvements were observed in crack width control at the failure stage. Specifically, type A nano-coating resulted in a 73.7% reduction in crack width compared to the uncoated fiber mixture. This substantial improvement highlights the potential of nano-coating to enhance ductility and post-cracking behavior, which is particularly beneficial in additive manufacturing applications where crack control is critical. The findings indicate that by improving fiber dispersion and matrix bonding, it may be possible to reduce fiber dosage while still achieving effective crack mitigation.

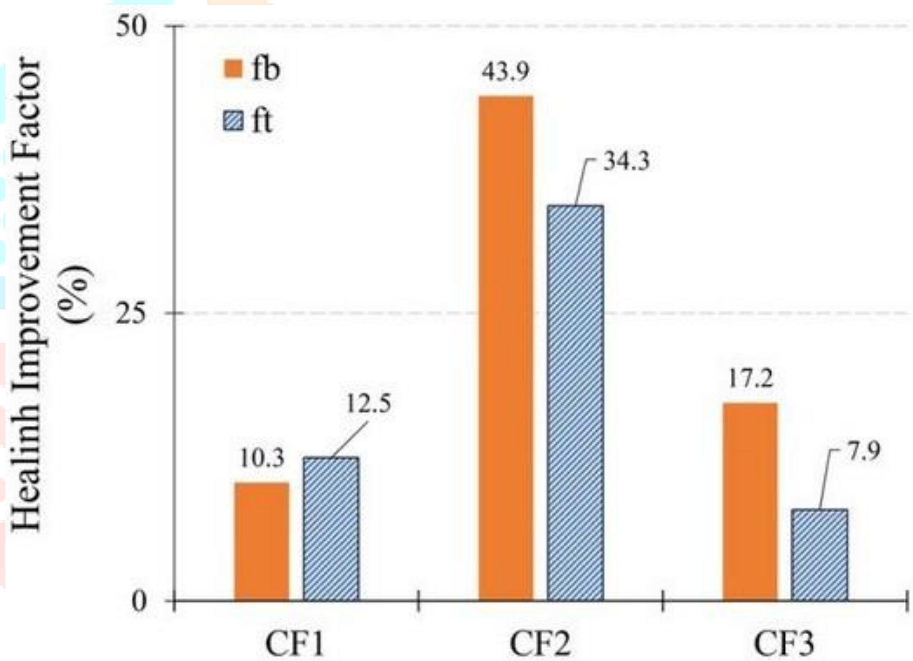


Figure 14. Healing improvement factors for mixtures containing nano-coated fibers.

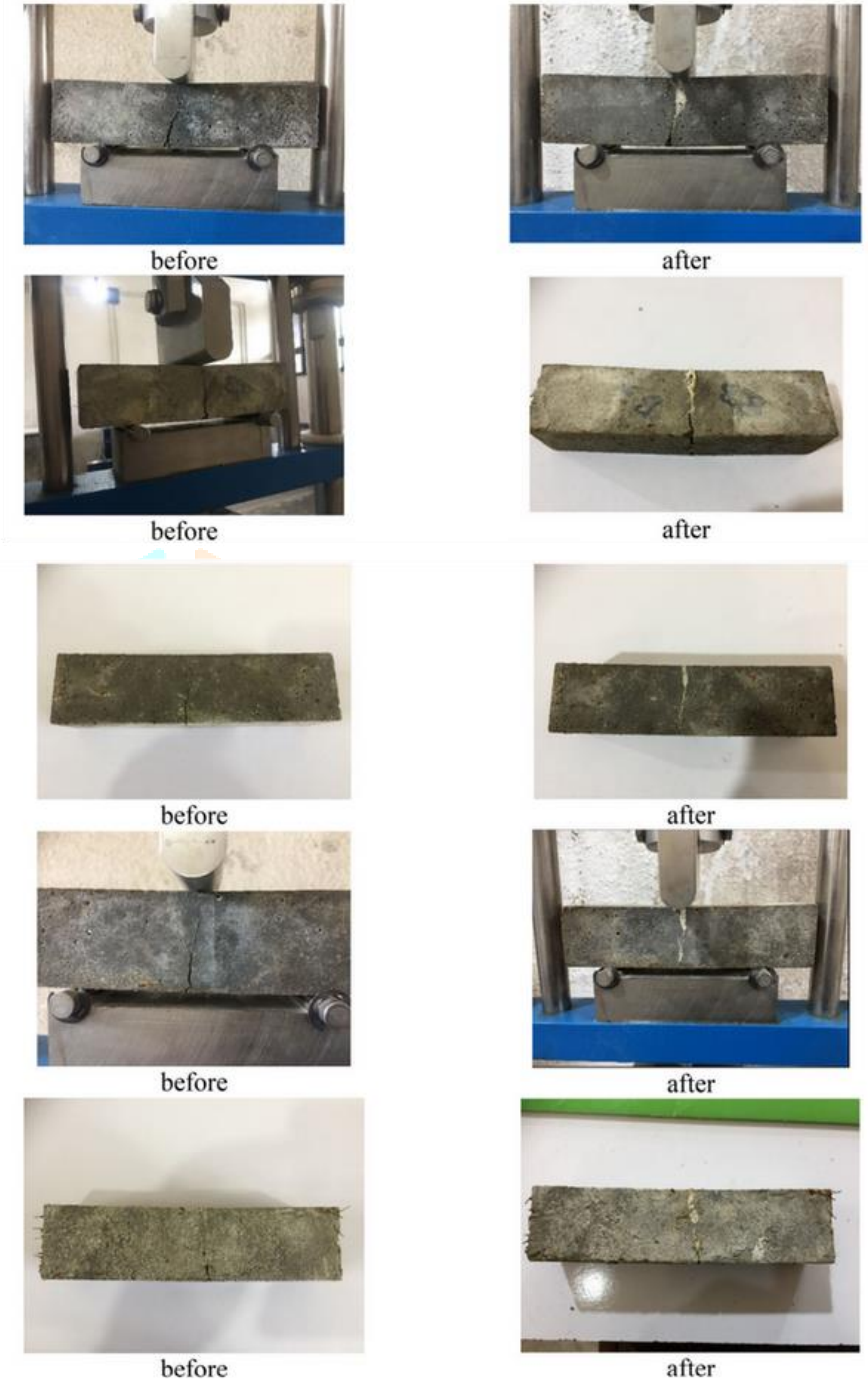


Figure 15. Crack sealing in flexural samples after the healing period.

4.4. SELF-HEALING POTENTIAL OF NANO-COATED FIBER MIXTURES

The self-healing capability of the nano-coated fiber mixtures was also evaluated. Test results demonstrated a strong potential for strength recovery after damage, with maximum healing improvement factors of 34.3% and 43.9% recorded for tensile and flexural strength, respectively. Notably, the CF2 mixture—employing type B nano-coating—exhibited the highest healing efficiency, despite showing comparatively lower initial mechanical performance. This suggests that the higher PVA content in the CF2 formulation may have delayed early hydration, leaving unhydrated cement particles available to contribute to healing upon moisture ingress. The role of GO in accelerating the rehydration process and promoting healing product formation was also considered significant.

While the experimental results demonstrate promising outcomes in both mechanical enhancement and self-healing performance, it is important to note that further experimental validation is necessary. Additional research is recommended to confirm the reproducibility and long-term durability of the self-healing behavior observed in this study. Moreover, the scope of future work should be expanded to include various types of fibers and alternative nano- coating formulations, which may provide further improvements in mechanical performance, cost-efficiency, and healing capabilities. Such investigations will contribute to developing more robust and sustainable 3D printable concrete technologies for structural applications.

4.5. Emerging Prospects and Futuristic Trends of 3D Concrete Printing Technology in the Indian Construction Industry

3D Concrete Printing (3DCP) is transforming the way we think about building and construction. Instead of relying on bricks, mortar, and manual labor, this technology uses large automated printers to layer specially designed concrete according to a computer-generated design. The process eliminates the need for traditional formwork and speeds up construction while maintaining precision and strength. The concrete used in 3D printing is no ordinary mix — it's engineered to flow easily through the printer, set quickly, and maintain structural stability.

India has already made impressive progress in adopting this futuristic technology. In 2021, Tvasta Manufacturing Solutions, a start-up from IIT Madras, built the country's first 3D-printed house in just five days using locally developed materials. Soon after, Larsen & Toubro (L&T) Construction achieved another milestone by completing India's first two-storey 3D-printed building in Kanchipuram, Tamil Nadu. Habitat for Humanity India, in partnership with Tvasta, went a step further by developing India's first 3D-printed community house in Chennai to help tackle the growing need for affordable homes. The government has also shown strong support for this innovation, with pilot projects under the Pradhan Mantri Awas Yojana (PMAY) exploring the potential of 3D- printed housing in Ahmedabad. These examples show how 3D printing is no longer just an experimental technology—it's becoming a practical solution for real-world construction challenges.

The possibilities for 3D concrete printing in India are immense. Beyond housing, this technology could soon be used to construct bridges, pavements, retaining walls, and other infrastructure components with unmatched precision and speed. The combination of Artificial Intelligence (AI) and Internet of Things (IoT) technologies will make the process even smarter—AI could predict structural behavior or fine-tune material flow, while IoT sensors could monitor curing and material quality in real time. Researchers are also exploring self-healing concretes that can repair small cracks on their own, extending the lifespan of printed structures. From an environmental standpoint, 3DCP offers a huge advantage by cutting down on material waste, reducing CO_2 emissions, and allowing the use of eco-friendly materials such as recycled aggregates and geopolymer concrete.

5. CASE STUDY

1. Babol University, Iran – Key Case Study

- Objective: Tackle issues of high microfiber content in concrete (which adversely affects flow, porosity, cost) by using a GO–PVA nano-coating on micro steel fibers.
- Mechanical Tests: Evaluated compressive, direct tensile, and bending strengths.
- Method: Steel fibers were coated via PVA-assisted deposition of GO nanosheets. This produced nano-coated fibers integrated into 3D-printable mortar.

2. Concretene – Graphene-Enhanced Concrete Slabs (UK)

- Developed by Nationwide Engineering Research & Development (NERD) and University of Manchester's GEIC.
- Used in actual pours including a gym floor slab in Amesbury (April 2021), a parking/loading bay at GEIC (Sept 2021), and a suspended floor deck at Manchester's Mayfield Depot in October 2021.
- Delivers improved compressive/tensile/flexural strength, faster curing, and lower permeability all by simply adding a graphene admixture at batching stage.

3. RMIT & University of Melbourne Demonstration (Australia)

- Researchers added a tiny amount of graphene oxide (0.015 wt%) to 3D-printed cementitious mortar.
- Resulted in ~10% increase in compressive strength and significantly better inter-layer bonding.Additionally, imparted electrical conductivity, opening doors to "smart walls" capable of crack detection

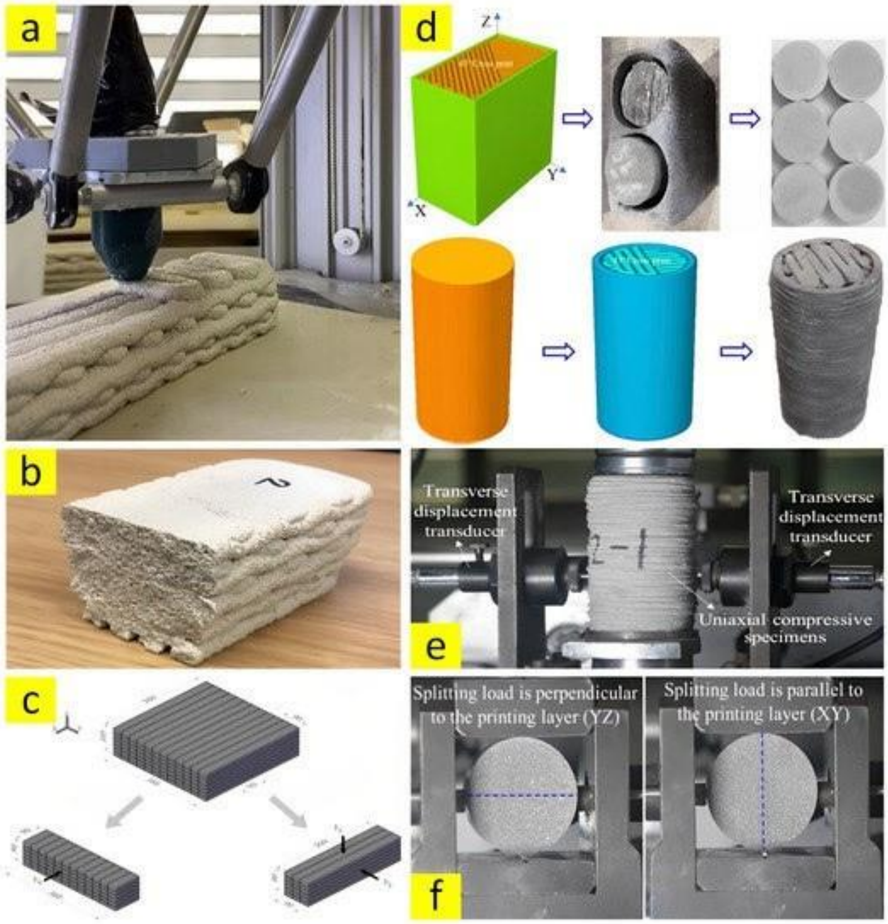


Figure 16. 3D printing of concrete structures.

REFERENCES

1. Yang Y, Wu C, Liu Z, et al. 3D-printing ultra-high performance fibre- reinforced concrete under triaxial confining loads. Addit Manuf. 2022;50:102568. doi: 10.1016/j. addma.2021.102568.
2. Zhou J, Lai J, Du L, et al. Effect of directionally distributed steel fibre on static and dynamic properties of 3D printed cementitious composite. Constr Build Mater. 2022; 318:125948. doi: 10.1016/j.conbuildmat.2021.125948.
3. Singh A, Liu Q, Xiao J, et al. Mechanical and macrostructural properties of 3D printed concrete dosed with steel fibers under different loading direction. Constr Build Mater. 2022;323:126616. doi: 10.1016/j.conbuildmat.2022.126616.
4. Zhou Y, Jiang D, Sharma R, et al. Enhancement of 3D printed cementitious composite by short fibers: a review. Constr Build Mater. 2023;362:129763. doi: 10.1016/j.conbuildmat.2022.129763.
5. Giwa I, Game D, Ahmed H, et al. Performance and macrostructural characterization of 3D printed steel fibre reinforced cementitious materials. Constr Build Mater. 2023;369: 130593. doi: 10.1016/j.conbuildmat.2023.130593.
6. Han B, Ding S, Wang J, et al. Nano-engineered cementitious composites: principles and practices. Springer, Singapore; 2019.

7. Bhojaraju C, Mousavi SS, Ouellet-Plamondon CM. Influence of GGBFS on corrosion resistance of cementitious composites containing graphene and graphene oxide. Cem Concr Compos. 2023;135:104836. doi: 10.1016/j.cemconcomp.2022.104836.

8. Mousavi SS, Mousavi Ajarostaghi SS, Bhojaraju C. A critical review of the effect of concrete composition on rebar–concrete interface (RCI) bond strength: a case study of nanoparticles. SN Appl Sci. 2020;2(5):893. doi: 10.1007/s42452-020-2681-8.

9. Mousavi SS, Bhojaraju C, Ouellet-Plamondon C. Clay as a sustainable binder for concrete—a review. Construct Mater. 2021;1(3):134–168. doi: 10.3390/constrmater1030010.

10. Mousavi SS, Dehestani M. Influence of mixture composition on the structural behaviour of reinforced concrete beam-column joints: a review. Structures. 2022;42:29–52. doi: 10.1016/j.istruc.2022.05.115.