

# State of the art of 3D printing of concrete in construction: Materials

Stadiul actual al imprimării 3D a betonului în construcții: materiale

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**Abstract** The paper provides an overview of current studies on 3D concrete printing, highlighting its transformative impact on traditional construction methods. It begins by reviewing advancements in materials specifically tailored for this technology, including fibers, binders, aggregates, additives, and admixtures essential for printed concrete. The article notes that 3D concrete printing requires special mortars that facilitate extrusion, set rapidly, and ensure strong mechanical performance while minimizing environmental impact. The focus is on the unique properties of these materials, differing from conventional concrete, such as rheology, durability, rapid setting, and a reduced carbon footprint, which are critical for additive manufacturing processes. Despite technological progress, challenges remain regarding the long-term mechanical behavior, material durability, and process consistency of 3D printed elements. The conclusion underscores the need for further research to overcome these obstacles and asserts that 3D concrete printing represents a promising pathway toward more automated, adaptable, and sustainable construction practices.

**Keyword:** 3D concrete printing, fiber reinforcing, the materials, technological advancements, material durability.

## 1. Introduction

The U.S. government, mainly NASA and the military, supports 3D printing for the development of rapidly deployable and sustainable space infrastructure. COBOD promotes 3D printing as a low-carbon alternative within the framework of the European Green Deal. China is leading in Asia in large-scale housing thanks to Winsun, while India is experimenting with it for affordable housing. 3D printing is expanding across Africa, as shown by Kenyan schools built by NGOs [1].

A thorough examination of Google Scholar, Web of Science, and Scopus was also required for the review. We used specific terms like 3D concrete printing, additive manufacturing in the construction sector, digitally created concrete, and rheology of

printable concrete. This careful research method covered a wide range of scholarly articles, conference presentations and journal papers published between 2010 and 2024, demonstrating the quick evolution and expanding academic interest in this topic [2]. In preliminary research for this review, 1,033 3D concrete printing papers were found. Subdivisions were established for sustainable materials (400 articles), structural topology optimization (472 articles), and tool path design (161 articles) [3]. This rise in publications, especially after 2020, shows the acceleration of 3D concrete printing (3DCP) research, showing its expanding importance and the concerted international effort to enhance its potential [4]. The rise in research between 2016 and 2019, and again after 2020, shows that 3D printing has the ability to transform the building industry by solving major issues like material waste and energy usage [5]. ALAMI et al. [6] discuss how 3D concrete printing (3DCP) could transform the building industry, especially for UN Sustainable Development Goals (SDGs). They claim that 3DCP may lower costs by 78% and water use by 60% compared to conventional methods. It might cut global energy use by 5% by 2025, making it a sustainable powerhouse. Even though 3DCP has less climate impact, its sustainability needs improvement. The authors emphasize the importance of ongoing research and development to overcome current limits and maximize 3DCP's industry benefits .

## 2. TECHNOLOGIE

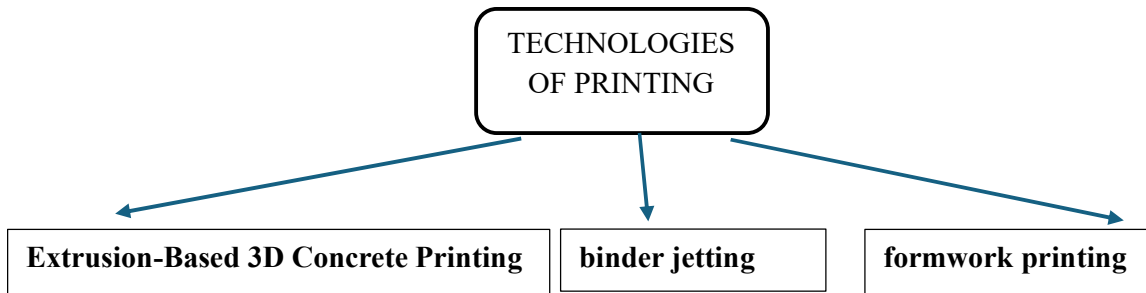


Fig.1. The most commonly used printing technologies

### 2.1 Extrusion-Based 3D Concrete Printing

Compared to traditional construction, extrusion-based 3D concrete printing (3DCP) increases efficiency, design flexibility, and environmental sustainability. It speeds construction, decreases labor costs, and allows complicated geometries that conventional approaches cannot.

3D printing with extrusion is a quickly developing technology in the building sector [7]. Complex buildings and customized design solutions can be efficiently produced using extrusion-based 3D concrete printing due to its design flexibility, reduced manual labor, little material waste, and high automation via building information modeling (BIM) [8]. Construction applications for Extrusion-Based 3D Concrete Printing (3DCP) innovation are vast and significant. This technology boosts efficiency, sustainability, and design flexibility.

### 3.2 binder jetting

Binder jetting technology (BJT) in 3D printing concrete improves mechanical performance, adaptability, and sustainability. Sustainable construction approaches benefit from effective material use, including recycled aggregates. BJT can precisely produce complex geometries, making it perfect for architectural and construction applications.

ODAGLIA et al. note that Binder Jetting uses waste materials to create a circular economy and improve material characteristics, reducing CO<sub>2</sub> emissions by 30%. BJT technology will improve manufacturing efficiency and increase output volume by 50%. Achieving a 0% safety incidence rate makes this project crucial to the building industry's sustainability. [9].

3D concrete printing with BJT benefits the construction industry. It boosts efficiency, sustainability, and design flexibility. BJT is appealing for modern building due to these qualities.

### 2.3 formwork printing

Traditional formwork construction technologies struggle to achieve complex geometries and optimal designs. 3D printing can do so. Material characteristics and reinforcement integration issues limit its industry adoption.

Formwork building with 3D printing improves load-bearing capacity, rigidity, material efficiency, and speed. However, stress concentrations over tensile limits require reinforcement in critical areas to prevent failure. [10]

3D printing can transform formwork building, but the industry must address its constraints. For wider adoption, innovation and established methods may need to be balanced.

## 3. Materials

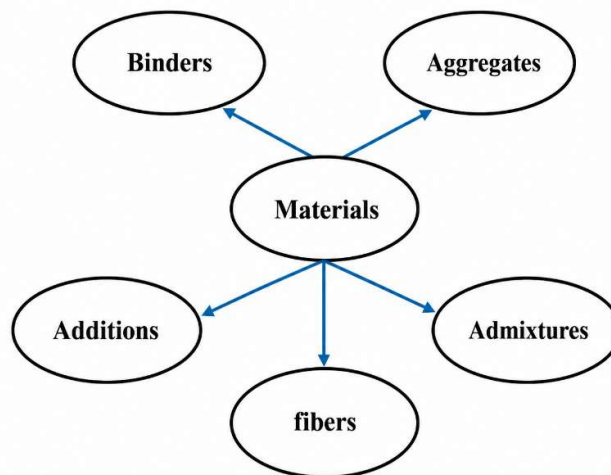


Fig. 2. The different types of materials used in 3D concrete printing

### **3.1. Binders**

#### **3.1.1 Traditional hydraulic binders**

Research by BRAHIM A et al. explores the properties of 3D-printed Portland Pozzolana Cement (PPC) concrete, highlighting its sustainability and cost-effectiveness as an alternative to traditional Portland cement (OPC). PPC, incorporating 35% fly ash, is evaluated for its structural integrity and essential qualities such as extrudability, printability, and thixotropic open time, aiming to enhance eco-friendly construction methods [11].

MAROSZEK et al. note the increasing demand for cement-based concrete driven by urbanization, yet emphasize the environmental challenges posed by resource depletion and greenhouse gas emissions. They suggest that using industrial waste and recycled aggregates can substitute concrete while achieving controlled mechanical performance. Their analysis indicates that recycled 3D printing concretes can reduce CO<sub>2</sub> emissions by 20-50% while maintaining structural performance [12].

LUO et al. examined how carbonation duration affects the mechanical characteristics and interfacial bonding of 3D printed cement-based material using 100% carbonated recycled sand. Carbonation time reduced mechanical anisotropy in printed specimens but did not remove it. As carbonation time extended, the interlayer shear strength and interstrip shear strength increased by 21.5% and 18.7%, respectively, improving interfacial bonding performance [13].

#### **3.1.2 Binders based on complementary materials (partial cement substitutes)**

##### **3.1.2.1 fly ash (FA)**

The study by COLYN et al. reveals that 3D printed concrete with fly ash (FA) as a supplementary material exhibits 28-day compressive strengths of 31 to 55 MPa and elastic moduli of 29 to 37 GPa. Their mixtures, containing 60% alternative binders including FA, not only showed suitable rheological properties for 3D printing but also produced smooth surfaces with no visible cracking, indicating improved performance and sustainability [14].

OVER et al. investigated eco-friendly 3D printed mixes using fly ash, granulated blast furnace slag, and marble dust. They also studied how VMA and silica fume affected their characteristics. In the study, SF increased fresh qualities and VMA mixes had greater static yield strength. The FA-SF blend was best for printability and sustainability, considering environmental impacts and engineering properties [15].

TSENG et al. studied 3D-printed concrete printing and hardening. They replaced cement in 3DPC with fly ash and crushed granulated blast furnace slag in various ratios. FA and GGBFS were tested for extrudability and buildability on 3DPC's printing and toughened characteristics. All mix designs satisfied 3DPC's printing standards, with larger GGBFS-content specimens being stronger and heavier. FA and GGBFS can replace 50% of 3DPC cement [16].

VICO LUJANO et al. optimized mortar rheology, hydration kinetics, and structural performance for extrusion-based 3D printing with a novel formulation. After extrusion, potassium-rich biomass fly ash (BFAK) and air-entraining plasticizer (APA) increase yield stress, thixotropy, and structural stability. BFAK alters hydration kinetics, extending setting time, which APA controls. BFAK improves cohesion without dispersion by reducing spread diameter in flowability testing [17]. The maximum printed height is achieved by 1.5% APA and 2% BFAK, according to calibration cylinder tests, demonstrating its buildability and load-bearing capacity. This synergistic effect promotes sustainable cementitious materials by customizing fresh-state properties and structural dependability [17].

LI et al. tested FAM-nanosilica 3DP mortars. Optimization of water reducer dosage enhanced extrudability, buildability, and dimension stability. The w/cm ratio, FAM, and NS concentration defined 3DP mortar's mechanical qualities. FAM and NS boosted flexural, compressive, and bond strengths, suggesting they should improve 3DP mortar design together. [18].

Fly ash as a cementitious ingredient in 3D printed concrete increases mechanical characteristics and reduces CO<sub>2</sub> emissions and energy use. Mixture composition and fly ash proportion affect these qualities.

### **3.1.2.2 Ground Granulated Blast Furnace (GGBS)**

3D concrete printing (3DCP) and fresh and hardened performance were studied by ALI et al. Adding GGBS and SC to 3DCP mixes as partial substitutes for Portland cement and natural sand increased flowability, extrudability, and buildability. The best blend was 30% GGBS and 20% SC, with 28-day compressive and flexural strengths of 50.61 and 6.73 MPa, respectively. In 3DCP, GGBS and SC can improve environmental effect and structural performance without affecting printability, according to the study [19].

SI et al. examine how nano-silica (NS) and high GGBS replacement levels affect 3D printed concrete's mechanical characteristics and rheology. NS improved rheological behavior, compressive strength, plastic viscosity, and thixotropic characteristics. At 28 days, C3G7N1, the best mix, had 105 MPa compressive strength, exhibiting greater mechanical performance and decreasing carbon footprint for sustainable 3D concrete printing [20].

MISHRA et al. investigated using GGBS and fly ash in 3D printing mortar to minimize OPC consumption. Four mortar mixtures were tested for printability. The best blend, O70G30 (70% OPC, 30% GGBS), retained shape 18.3% and 54.3% better than the control and O70F30 mixes. Due to its finer particle size and larger specific surface area, GGBS had 22.2% less open time than the control. The printed specimens have anisotropic compressive strength 9.4–35.6% lower than mould-cast samples. GGBS improved hydration, microstructure, and 3D printed mortar performance [21].

The incorporation of fly ash in GGBS 3D printed concrete enhances its mechanical properties and promotes sustainability. Optimal material combinations lead to concrete

with superior compressive, flexural, and tensile strengths compared to conventional concrete, while also reducing carbon emissions from cement production.

### **3.1.2.3 Silica Fume**

NASSRULLAH et al. adapted 3D printing systems with carbon nanotubes (CNTs) and silica fume to explore cementitious composites. According to tests, adding 0.2% CNTs and 20% silica fume improved the rheology, buildability, open time, and printing quality. While buildability and open-time increased by 201% and 263%, respectively, layer width and height error decreased from 140% and 6% to less than 1.5%. With CNTs and silica fume, cast and 3D-printed samples had better compressive and flexural strengths [22].

According to PANTIRU et al. Incorporating silica fume as a cement replacement in 3D printed concrete enhances strength, durability, and workability, optimizing fresh properties and promoting a more sustainable construction method while reducing concrete production's carbon footprint [23].

THAJEEL et al. examined how metakaolin (MK) and silica fume (SF) affect 3D printed concrete. Increased MK content enhanced early strength increase, shape retention, and buildability, the study revealed. However, large MK doses created cracking and extrudability issues. The optimal blend was MK10SF5, with 10% MK and 5% SF for shape retention, buildability, and compressive strengths. MK and SF synergistically increased particle packing, cohesion, and pozzolanic reactivity, suggesting they might optimize 3DPC for printability and mechanical performance [24].

In order to enhance the printability and mechanical performance of 3D printed magnesium phosphate cement (MPC), WANG et al. investigated the use of silica fume (SF). Through the formation of compact flocculation structures, SF was found to increase viscosity and yield stress. It also improved interlayer bonding, which decreased mechanical anisotropy. Additionally, the work demonstrated the failure mechanism of 3D printed MPC loaded in various loading directions and confirmed the impact of interlayer bonding on anisotropic behavior [25]

Silica fume usage improves 3D printed concrete's rheology and strength. Silica fume, a pozzolanic substance, has a denser microstructure, which is needed for 3D printing with high compressive and flexural strengths.

### **3.1.3 Geopolymer**

Comparing additive building to traditional methods, AHMED et al. report accurate material deposition, reduced waste, more design freedom, and faster manufacturing. Concrete buildings pollute due to Portland cement manufacturing's energy and greenhouse gas emissions. To solve these issues, AHMED et al. study geopolymer concrete, a cement-free, eco-friendly option made from industrial wastes. Custom

geopolymer concrete mixtures, printability for 3D building designs, and hardened properties will be tested. Raising slag concentration boosts compressive strength, activator temperature improves printability, and idle time before printing improves uniformity [26].

YOUSSEF et al. found that because of its low Si/Al ratio, BFS amorphe, which contains 31% CaO and 42% SiO<sub>2</sub>, requires a significant amount of sodium silicate. MK and BFS have been used in combination to lessen the environmental impact. The addition of a superplasticizer has decreased the mixture's weight loss and calcium carbonate content [27].

SILVESTRO et al. examined how low-carbon binders like CSA, LC3, and geopolymers affect concrete characteristics, mechanical performance, and durability. They found that CSA cement's composition and particle size greatly affect cementitious mixture viscosity and structural build-up. Metakaolin and limestone LC3 cements have good mechanical performance and sustainability, whereas geopolymeric binder has compressive strengths comparable to or greater than OPC [28].

GPC has compressive strength up to 50 MPa, compared to 40 MPa for OPC concrete. Tensile strength increases from 4.0 to 5.5 MPa and flexural strength from 6.0 to 8.0 MPa. GPC outperforms concrete in sulfate attack, chloride intrusion, thermal stress, and acidic conditions by 20% [29].

The use of waste concrete fine aggregates (WCA) in geopolymer mortar for 3D concrete printing is investigated by KRAVCHENKO et al. as a sustainable substitute for traditional building techniques. Their findings demonstrate that, in comparison to natural fine aggregates (NFA), WCA-based mixes have improved compressive strength and dimensional stability. The life cycle assessment (LCA) indicates a 3.4% decrease in both terrestrial acidification and global warming potential as compared to NFA. The study also highlights how crucial orientation is for 3D printing, as it demonstrates notable increases in compressive strength in every tested direction [30].

Sustainable 3D-printed geopolymer concrete (3DPG) has been evaluated by ELHAG et al. as a low-carbon, environmentally friendly substitute for conventional building materials. Fresh properties, mechanical performance, and microstructural development are examined in relation to printing circumstances and basic components. The function of activators, supplemental materials, and reinforcing techniques in performance optimization is also covered [31]. Geopolymeric binder in 3D-printed geopolymer concrete has 20–70 MPa compressive strengths, depending on printing and curing [32]. MORTADA et al. examine how steel fiber affects 3D-printed Ca(OH)<sub>2</sub>-activated geopolymer concrete. 1.2% steel fiber increased flexural, tensile, interlayer bond, and elastic modulus. Slower shrinkage but no change in self-induced stress were found in durability tests. Microstructural investigation demonstrated steel fiber crack-bridging [33].

Advances in geopolymer utilization improve the mechanical properties of 3D printed concrete, enhancing printability, strength, and durability through optimized mixtures and additives, thereby improving the performance of geopolymer concrete (GPC) in 3D printing applications.

### 3.1.4 Gypsum 3d printing

3D-printing materials need viscosity modifiers. Huang et al. tested HPMC to ATP, NB, and NS in gypsum-based products. ATP, NB, and HPMC decreased slurry fluidity, whereas NS enhanced it at lower doses. Increasing yield stress increased plastic viscosity minimally in all VMAs. Compared to HPMC, inorganic VMAs reduced 2-hour wet and compressive strength loss. NS and HPMC reduced hydration exotherm peaks, while NB and ATP cut maximum peaks at 1% but caused early, higher peaks at higher dosages. Microstructural analysis showed that 0.5% HPMC produced flaky structures while 5% NS produced short, thick gypsum crystals. In conclusion, inorganic VMAs improve mechanical properties, workability, and performance in high-performance 3D printing gypsum materials[34].

Using 3D printing and gypsum based materials, XIANG et al. created advanced tunnel models and layered rock masses. Their research compared three innovative tunnel models to a traditional model and found that basic structures like inverted arch filling better simulate tunnel deformation and damage. Gypsum materials imitate tunnel failure under high in-situ stress, while 3D printing improves model precision. Under such load, tunnel vault and base collapse causes rock bending and shear-slip failures, according to study. To reduce damage, tunnel structures and rock at the bottom and vault must be reinforced[35].

TARAHAN et al. investigate using industrial gypsum byproducts PG and BG as partial cement substitutes in 3D-printed concrete to improve sustainability and printability. Adding 7.5% PG to ground granulated blast-furnace slag cement mortars resulted in the maximum strength (~51 MPa), surpassing the control. The fly ash system maintained control strength at 2.5% PG, but BG decreased strength at 7.5% or higher, suggesting 5%. Although BG-Fly Ash mixtures improved open time, PG mixes remained steady. The study found that PG dosages of 5-7.5% improve mechanical performance without affecting workability, while BG is indicated only for extended open time.[36].

### 3.1.5 Clay 3d printing

For building, urban furniture, maritime, and artistic purposes, large-format additive manufacturing (LFAM) uses cement and clay. Clay offers architectural freedom, while cement is structurally sound. Complex structural features require parametric design and high-performance clay materials. Architecture may be transformed by digital technologies to create complex forms that improve aesthetics and performance. Design flexibility, energy efficiency, and environmental impact can be improved by LFAM and parametric and generative design. Interdisciplinary collaboration, structural analysis, printing control, maintenance planning, and stakeholder approval are challenges. A parametric design study with Grasshopper shows façade panel geometry, verifying its application for facade component manufacturing [37].

Rapid population increase has caused a global housing crisis. GONSALVES et al. note that additive manufacturing (AM) or 3D printing can address this issue because to its shorter building periods and design flexibility, although slow-setting concrete and

cement's environmental impact are drawbacks. They present a clay-based construction material that hardens quickly after printing and has concrete-like characteristics. This material's thermally triggered frontal polymerization sets immediately, allowing multilayer walls and complicated shapes. It reaches 3 MPa buildable strengths immediately after printing and exceeds the 17 MPa required for residential concrete in 3 days, compared to 28 days for standard concrete. The methods show promise for sustainable infrastructure construction [38].

### 3.1.6 Hybrid and innovative binders

Due to reduced manual labor and resource efficiency, concrete 3D printing has grown worldwide over the past decade. Ternary gypsum–cement–pozzolanic (GCP) composites, developed by SAHMENKO et al., are water-resistant like Portland cement (PC) and harden quickly like gypsum. These composites exhibited compressive strength up to 37 MPa, comparable to typical PC mixes, and stability for printing up to 35 layers using recycled plasterboard gypsum and phosphogypsum. Life Cycle Analysis showed a 40% carbon footprint decrease over PC mortar, encouraging sustainable 3D printing[39].

Incorporating 5% silica fume and 50% GGBS in 3D printed mortars resulted in a compressive strength of 109.10 MPa and improved flexural strength, showcasing better mechanical properties through optimized silica fume use [40].

Concrete 3D printing is a potential automation technology, but little is known about how strong and durable it is. In contrast to mold-cast (MC) specimens, KAUR et al.'s study examined the durability of 3D printed concrete (3DPC) made with fly ash (FA) and limestone calcined clay (LC). The results demonstrated that the FA-based mix had improved pore structure and decreased porosity, which led to a higher compressive strength and less water absorption. Porosity and drying shrinkage were strongly impacted by the casting/printing procedure [41].

Silica fume, fly ash, blast-furnace slag, meta-kaolin, paper sludge fly ash, limestone powder, reactive ultra-fine fly ash, oyster shell powder, and calcium sulfate whisker were examined by XUE et al. Hydraulic activity and microscopic particle size improved printability without strength loss, but FA and BF had minimal effect. Even with 30% cement replacement, these materials remained strong, indicating optimal print quality and environmental benefits at <30% [42].

High-performance concrete additives made of graphene are appealing, but cost and industrial scaling concerns limit their application. According to SUREHALI et al. ultra-low doses of fractal graphene (FG) and reactive graphene (RG) affect the rheology of 3D-printable concrete. Functional groups in RG-modified mixes increase dynamic and static yield stresses and viscoelastic characteristics more than in FG-modified mixtures. After mixing for 30, 60, and 90 minutes, we discovered that ultra-low graphene dosages doubled construct heights. Important rheological parameters required for material supply, expansion, and layer build-up in concrete 3D printing are shown in this study using storage modulus and its development [43].

Advances in hybrid and innovative binders enhance the mechanical properties of 3D printed concrete by improving printability, reducing anisotropy, and optimizing interlayer bonding, addressing the limitations of traditional concrete in 3D printing applications.

### 3.2 Aggregates

PEPE et al. study 3D concrete printing (3DCP) focusing on sustainable raw material usage with recycled fine aggregates, achieving 100% recycled aggregate combinations without mechanical quality loss and promising compressive strength above 50 MPa [44].

Ma et al. explore the incorporation of recycled fine aggregate (RFA) and clay brick powder in 3DPC, noting reduced ambient compressive strength but improved high-temperature residual strength [45].

Jia et al. investigate recycled brick fine aggregates' impact on 3D printed concrete's plastic phase, finding that RBFA affects water evaporation and plastic shrinkage, suggesting specific additives for optimization [46].

Demirbaş et al. analyze 3D printable mixtures using Portland and white cement with (RCA), highlighting resulting high-strength mortars (70 MPa) and modest negative effects on water absorption compared to natural aggregates [47]. MIM et al. explored the use of copper heap leach residue (CHLR) as a fine aggregate in 3D printed concrete (3DPC), finding that while greater CHLR content enhances buildability, it also diminishes flowability [48].

LIANG et al. studied the shear modulus in various sands, revealing that irregular particle morphologies notably enhance the maximum shear modulus, with local roundness impacting its sensitivity to stress [49]. SHI et al. investigated marine coral sand-clay mixes with 3D-printed triaxial geogrid reinforcement, showing that higher confining pressure and more reinforcement layers significantly improve strength, providing insights for maritime engineering [50].

Using 3D-printed concrete waste, MENGISTU et al. evaluated (RAC). Researchers crushed 3DPC waste into fine and coarse aggregates with a jaw crusher. River sand and aggregates created C30/37 and C40/50 strength classes. The study tested compressive strength with destructive testing and rebound hammer. We observed that density gradually increases RAC compressive strength. Surface temperatures over 30°C reduced strength 11.5%. Except for C30-RA50, 50% and 67% recycled aggregate RAC combinations increased compressive strength [51].

LIU et al. examine pore structure and cold-weather 3D printed concrete durability. The researchers examined the impact of recycled coarse aggregate replacement ratios on 3D printed recycled aggregate concrete (3DPRAC) shape, mass loss, and dynamic elastic modulus under freeze-thaw cycling. 3DPRAC had lower F–T resistance to cast concrete, and its distinctive ellipsoidal pores and porous old mortar reduced its elasticity. The study also examined F–T resistance degradation methods based on pore structure, which could help cold regions use digital concrete manufacture [52].

MIM et al. examined the use of industrial by-products in 3D printed concrete (3DPC) for sustainable building, exploring materials such as mining wastes, seashells, and construction debris. The study assesses how these by-products influence the fresh, mechanical, and microstructural properties of 3DPC, suggesting a 20-40% substitution of fine aggregates to enhance strength and flowability while reducing waste and conserving resources [53].

Kumar et al. created earth-based 3D printed concrete (3DPC) instead of fine particles. They replaced 30–50% of natural sand with locally excavated 4% clay soil. Soil inclusion reduced printing flow and increased open time by 13-60% compared to the control mix. Increased extrudability and buildability allowed crack-free printing of over 30 layers. Crack onset was 30-50% slowed by soil addition [54].

WANG et al. investigated how paste-aggregate ratio and coarse aggregate content affect 3DPC properties to optimize mix composition and printing. Reduced paste-aggregate ratio increases static yield stress, dynamic yield stress, and plastic viscosity. Rheological characteristics and printing effect are best for concrete with a paste-aggregate ratio of 1.3. High coarse aggregate content degrades print quality. The best 3DPC performance is attained with 1.3 paste-aggregate ratio and 60% coarse aggregate. Cast concrete mechanical characteristics are less susceptible to specimen size than 3DPC [55].

China et al. developed a 3D concrete printing (3DCP) with high strength, low cost, and shrinkage. Their extrusion-based 3D printer printed 20mm-grain concrete. In the investigation, cement to aggregate volume ratio (C/A) affected printability and mechanical performance. The microstructure was analyzed using X-CT and SEM. Printable concrete's initial flowability should be 178-200mm, and its C/A should be 0.35-0.60. Non-uniform void distribution caused 3D printed specimens to have direction-dependent compressive and flexural strengths [56].

WANG et al. produced 3D printed concrete (3DPC) with coarse aggregates to improve performance. found that aggregate size diminishes extrudability, stabilizes, and reduces slump. Rheology and mechanical tests explain this. As aggregate particle size grows, 3DPC mechanical characteristics improve, and all groups show substantial anisotropy. Microscopic experiments showed 3DPC pores have directionality, explaining fracture mechanics anisotropy. Large coarse aggregates boost 3DPCAC compressive strength and elastic modulus but impair extrudability and increase anisotropy [57].

New construction approach using plastic trash by NAZIR et al. They improved self-compacting mortar (SCM) rheology utilizing 3D-printed plastic fine aggregates (3DPFA) and rheological testing equipment. Testing SCM mixes with different 3DPFA content showed considerable workability and flow benefits. With more 3DPFA, the mini-slump spread grew, T20 flow time decreased, and J-ring tests revealed better passing. Thermal conductivity dropped 22% and V-funnel flow time decreased. This shows a possible building plastic waste valorization path [58].

WANG et al.'s work investigates the application of (GGBFS) and ferronickel slag in 3D printing. The study discovered that while little aggregate size leads to insufficient yield stress, big aggregate size adversely impacts the smooth extrusion of concrete strips [59]. WANG et al. also discovered that the stability and quality of the printed concrete strips are impacted by the extrusion performance, which is strongly correlated with aggregate

size and nozzle diameter. 30% to 50% of the nozzle diameter is the maximum aggregate size suggested by the study for stable extrusion, 50% for smooth extrusion, and 30% for acceptable shape [59].

According to PARITALA et al. aggregate type, content, and paste rheology affect concrete mixture printability. They observed that higher yield stress paste mixes need additional paste to maintain fluidity, limiting aggregate content. Paste binder content depends on packing density and aggregate surface area. High-fine, low-sphericity mortar combinations need more paste despite increased packing density. Particles with irregular shapes and vast surface surfaces need more paste for flowability and coating. The investigation validated across aggregate types a unique linear relationship between paste yield stress and excess paste content. These proportioning instructions are for printed concrete compositions [60].

based on GIRSKAS et al. The most popular fine aggregate for the 3D printed concrete mixture is 0/2 mm fraction sand, which is the only fine aggregate utilized in its preparation. For 3D printed concrete, however, some studies show that 0/4 mm fraction sand and even coarse aggregates (crushed stone) of 4/8 mm fraction are feasible [61].

The mechanical properties of 3D printed concrete are significantly affected by the type and characteristics of aggregates, especially advanced aggregates. Important factors include aggregate size, type, and their interaction with printing parameters, which influence both printability and strength.

### 3.3. Additions

JIN et al. investigate how inorganic micro/nanomaterials can change the rheology and mechanics of cementitious composites in 3D concrete printing. Carbon-based, silicon-based, metallic oxide, and nano-calcium carbonate particles have been utilized in 3D printing concrete or may be employed in the future. The study also reveals the many uses that can result from combining 3D printing manufacturing methods with varied nanomaterial qualities [62].

According to BOS et al., additive manufacturing, particularly concrete (AMoC), has drawn more attention from the building sector. AMoC is still in its infancy even if a lot of scholars and private businesses are exploring this sector. 3D Concrete Printing (3DCP) at Eindhoven University of Technology is one of numerous AMoC versions being developed worldwide. 3DCP is compared to AMoC and 3D printing. They also study 3DCP product shape, structure, parameter relations, experimental research, and large-scale 3DCP application obstacles [63].

DAI et al. proved that 3D-printing may assist construction companies develop customized parts, remove formwork, and save materials. Pumpability, extrudability, and buildability of 3D-printed concrete are tricky. Fly ash (FA) accelerates portlandite-induced thermal stiffening and alkali-activation. CH-FA blends stiffen quickly at 75°C but build up less at low temperatures. The FA-CH mix ratio, ideally 20%, can develop cement-free 3D-printing compositions [64].

CAVALCANTE et al. investigated using recycled concrete powders (RCP) to minimize 3D printing cement. The study indicated that RCPs improve 3D printing rheology

depending on origin. RCP pastes of any origin showed elevated static and dynamic yield stresses and early hydration. RCP paste viscosity changed with packing density, and increased yield stress can impair extrudability and buildability. The LCI assessment suggested RCPs may reduce CO<sub>2</sub> emissions by 62%. RCPs could be used to make environmentally friendly 3D printed combinations with rheological changes [65].

NASSRULLAH et al. modified 3D printing systems with carbon nanotubes (CNTs) and silica fume to research cementitious composites. Testing indicated that 0.2 % CNTs and 20% silica fume increased printing quality, buildability, open-time, and rheology. Layer width and height error dropped from 140 % and 6% to less than 1.5 %, while buildability and open-time rose by 210 % and 263%. Both cast and 3D-printed samples had stronger compressive and flexural strengths with CNTs and silica fume. It also found that silica fume filled cement matrix gaps and CNTs formed nanoscale connections [66].

### 3.4. Admixtures

based on GIRSKAS et al. The workability, adhesion, stiffness, short setting time, and high early strength of 3D printed concrete are all controlled by chemical admixtures such superplasticizers, viscosity-modifying agents, setting retarders, and accelerators [67].

CO<sub>2</sub> mixing affects cement mortar with different concentrations of Polycarboxylate superplasticizer (PCE) and hydroxypropyl methylcellulose. Results reveal that CO<sub>2</sub> mixing considerably alters HPMC and PCE effects on cement mortar characteristics. PCE practically disappears, however 0.2 %PCE improves workability and setting time. To explore coupling effects, heat evolution and microstructural features are analyzed. We propose employing CO<sub>2</sub> mixing and PCE to improve 3DPC buildability (Fig 3) [68].

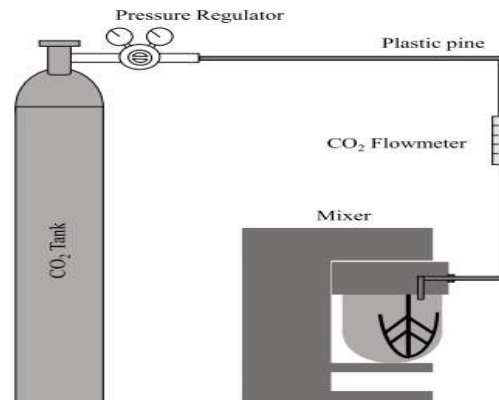


Fig.3. Schematic of the CO<sub>2</sub> mixing system [68].

GURUNANDAN et al. examined how water-to-binder ratio, admixtures, and increasing a/b ratio affect 3D-printable concrete mixture extrudability, buildability, and mechanical qualities. The study indicated that w/b ratio increased extrudability but decreased buildability. Adding fly ash improved extrudability, but increasing a/b ratio increased

surface imperfections and decreased it. Extrudable and buildable combinations had lower compressive strength than mold cast specimens and 2.1-2.6 kPa static yield stress. The printed specimens were not anisotropic in compression, and sequential layers had no weak joints. The findings could help create 3D-printable combination design recommendations [69].

Polysaccharides were added to alkali activated materials (AAMs) to improve their 3D printing properties in a comprehensive rheological investigation by SHILTON et al. AAMs are popular in construction, however printability and buildability issues prevent their use. Shirley et al. examined how Xanthan Gum (XG) concentration affected rheology, printability, and mechanical characteristics. The results are useful for developing a rheology-modifying admixture for AAMs, which will improve 3D printing without affecting setting times or compressive strength [70].

3D-printed concrete (3DPC) reduces labor costs, material waste, and building time, although its durability is still questioned. The layer-by-layer manufacturing technique affects material characteristics and durability. Interfacial porosity and anisotropic microstructures can weaken structures and make them more susceptible to environmental degradation. Increased layer interface porosity and shrinkage-induced cracking impair durability. Proper mix formulations and air-entraining agents can make 3DPC as durable as cast concrete. Additional cementitious components have improved chemical resistance [71].

ANOP et al. study investigates the use of conventional 70 mm cubes as a trustworthy indicator of in situ compressive strength in additive manufacturing. Compressive strengths were assessed after seven, fourteen, and twenty-eight days after five Portland cement mixtures were extruded into wall blocks using a 3D printer. Although the ratios between the core and cube strengths stayed constant, the core strengths were constantly inferior. For the non-destructive strength evaluation of 3D-printed concrete, the findings offer a straightforward, empirically supported procedure that opens the door for future standardization of quality-control procedures in additive construction [72].

### **3.4.1 Superplasticizer**

The study by FELIPE et al. studied the impact of water/cement ratio and superplasticizer % on the use of LC<sup>3</sup>-25 mortars in 3D printing. Results indicated that 75% metakaolin and limestone filler mixes were lighter than 100% Portland cement. Over time, superplasticizer (SP) increased air incorporation and distributed loss. In ternary mixes, SP level between 1% and 1.50% did not alter mechanical strength. The study recommends researching eco-friendly 3D printing materials [73].

By altering the dosage of superplasticizer and the water/binder, JANANI et al. created a 3D-printable concrete mix. They also replaced cement with 10% leftover marble powder. The process include modifying methods, material fineness, and mix proportions. The mix was improved through experimental studies with a 3D printer; the best combination with a dose of 0.35% SP, a ratio of 0.35 w/b, and a substitution of 10% marble powder produced excellent printing quality [74].

MAHMOOD et al. identified four research themes regarding recycled waste materials in 3DPC. They highlighted the importance of assessing physical and chemical properties, buildability, and the impact of additives like HPMC and superplasticizers on performance. Their findings indicate that higher cement content in 3D printed concrete can be economically and environmentally harmful, emphasizing the need for standardized testing and improved integration of designed architectural shapes [75].

DONG et al. used aeolian sand and ferrochrome slag to improve 3D printed concrete (3DPFAC). They used one-way testing to examine how critical materials affect 3D printed concrete (3DPC) operating and mechanical qualities. Silica fume, superplasticizer, polyvinyl alcohol powder, and polypropylene fiber were tested orthogonally. Silica fume 7%, superplasticizer 0.6 %, polyvinyl alcohol powder 1.2 %, and polypropylene fibers 0.2 % were the best combinations [76]. Experimental validation indicated the improved material had good printability, uniform extrusion, smooth surface, and low height variation. 3DPFAC was more easily destroyed by external force due to its higher interfacial microcracks between layers, lower hydration degree, and evident fiber-matrix fissures [76].

Superplasticizers enhance the workability and rheology of 3D printed concrete (3DPC) by modifying flow characteristics and reducing viscosity, thereby facilitating essential extrusion and layering processes for successful 3D printing.

### 3.4.2 Viscosity agents

The construction industry is adopting automatic construction technology, especially 3D printing. This process is fast, eco-friendly, and architecturally flexible, however 3D-Printed Concrete (3DPC) has extrusion difficulties. PRATHIPATI et al. investigated how Viscosity Modifying Agents (VMAs) can improve 3DPC printability and structural integrity by altering its rheological properties. Results show that controlling VMA concentrations improves 3DPC mixture workability and buildability, which has major implications for concrete additive manufacturing technology [77].

SHOAEI et al. compare suspension and paste microfibrillated cellulose (MFC) with hydroxypropyl methylcellulose powders as viscosity-modifying agents (VMAs) for 3D-printable Portland cement mortars. MFC mortars had higher workability, mechanical strength, denser microstructure, viscosity, and yield stress than HPMC. While HPMC mortars were marginally more extrudable, MFC was more shape stable. Both types of 3D-printed samples demonstrated 40% lower compressive strength than mold-cast samples but equivalent flexural strength. MFC paste was the best VMA for shape stability and printability [78].

To assess their suitability for use in 3D printing gypsum building materials, Huang et al. contrasted three inorganic viscosity modifier admixtures (VMAs) with hydroxypropyl methylcellulose ether (HPMC): attapulgit (ATP), sodium bentonite (NB), and nano-silica (NS). According to the results, NS increased slurry fluidity at low dosages, but ATP, NB, and HPMC decreased it. While all VMAs raised yield stress, inorganic VMAs barely affected plastic viscosity. Superior workability, mechanical characteristics, and

printing performance were displayed by ATP, while NS was excellent at improving mechanical properties and NB enhanced workability and performance [79].

The buildability of cement-based mortars made with nanoclays (NC) and viscosity-modifying admixtures (VMA) was investigated by MARQUEZ et al. They discovered that RMA has a major impact on CBM's buildability and hydration processes. NC improved buildability and dimensional stability by exhibiting a stiffening effect. Although more superplasticizer was required, NC dominated the shear stiffening effect when coupled. Setting and initial hardening after 90 minutes were linked to the change from fresh plastic behavior to a stiff state [80].

Viscosity agents affect 3D-printed concrete's workability, strength, and printability. VMAs increase concrete rheology, which is necessary for 3D printing.

### 3.4.3 Accelerator

Accelerators affected the rheology of 3D printed concrete (3DPC) with cellulose microfibers, according to CHO et al. CMFs reduce shrinkage and damage but delay setting, limiting 3DPC structuration and buildability. The study investigated 16 cement composites with different CMF and accelerator concentrations. CMF presence increased dynamic yield stress by 18% and plastic viscosity by 12%, while static yield stress was unaffected. The accelerator enhanced static yield stress by 290% and structuration rate by 400%. To improve 3DPC buildability and combat CMF deterioration, accelerators are recommended [81].

Active management of limestone calcined clay cement (LC3) paste fluidity and adjustable structural build-up improve subterranean shotcrete and 3D-printed concrete applications. JI et al. study LC3 paste fluidity and structural build-up using a non-alkaline accelerator and polycarboxylate ether (PCE) superplasticizers and retarders. The study found that high PCE dosages or lower PCE with a retarder can sustain fluidity for 6 hours. In high-PCE mixes, early accelerator addition accelerates ettringite production and structural acceleration, affecting penetration force and modulus. In situ XRD, heat release analysis, differential thermal gravimetry (DTG), and scanning electron microscopy were used to evaluate rheological behavior and microstructural development [82].

The use of advancement accelerators in 3D printing concrete enhances efficiency, sustainability, and design flexibility in construction projects, improving overall processes and outcomes.

### 3.4.4 Retarder

SENF et al. creates concrete mixes utilizing calcium sulfoaluminate (CSA) cement and blast furnace cement (CEM III/B) for 3D printing in response to environmental issues caused by regular Portland cement. In comparison to combinations without retardation, retarders specifically, a 0.60 weight percent mixture of tartaric acid and phosphate optimize the setting time for a 90-minute 3D printing window, resulting in early compressive strengths of about 96% and 28-day strengths of around 55%. According to

analyses, the slower hydration of Portland clinker and CSA is the cause of the 28-day strength decrease. When stresses were applied perpendicularly to printed layers, the application of 30 weight percent CSA and 70 weight percent CEM III/B demonstrated enhanced compressive strengths. Because of regulated setting, early strength, and steady long-term strength development, these findings encourage the efficient manufacture of precast concrete parts [83].

The use of retarders in 3D printing concrete improves material performance by extending the setting time, enhancing workability, and reducing temperature stress, which is vital for large-scale printing. This overview will examine the types of retarders, their advantages, and their effects on the mechanical properties of 3D printed concrete.

### 3.5. fibers

#### 3.5.1 steel fibers

In order to increase the flexural strength, toughness, and stiffness of mortar beams, LI et al. have created a two-scale technique utilizing 3D concrete printing (3DCP). Three patterns—rectangle, triangle, and Hilbert curve are used to generate steel fiber reinforced 3DCP infills. According to four-point bending tests, a rectangular arrangement of steel fibers enhanced flexural strength and toughness by more than 100%, while a triangular configuration resembling a truss boosted flexural stiffness by 59%. Additionally, the technique showed that it was possible to create structures with planned interior designs that were material-efficient [84].

A method for in-situ magnetization of steel fibers in 3D printed concrete is proposed by HUANG et al. with the goal of enhancing crack-bridging capacity. They look at the connection between fiber magnetic orientation and crucial process parameters (Fig 4). According to the results, 25mm bow steel fibers (BF25) significantly improve mechanical characteristics by more than 50% and have the greatest impact on bridging cracks. This demonstrates how fiber magnetic orientation can be used in 3D printed engineering concrete (Fig 5) [85].

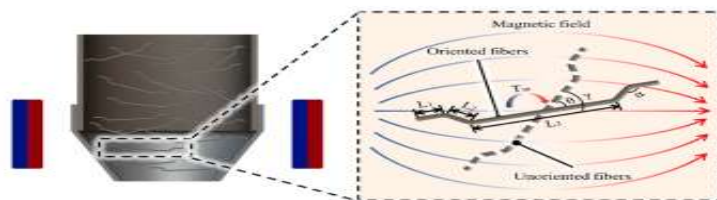


Fig 4. Schematic diagram of steel fiber orientation in magnetic field [85].



Fig 5. Schematic illustration of fiber alignment evaluation in concrete [85].

3D printing ultra-high performance concrete (UHPC) reduces structural steel reinforcement, according to CHEN et al. Their study examined how water-to-binder ratios, recycled steel fibre (RSF) volume, and thickener concentration affected RSF-reinforced UHPC rheology and extrudability. Lower water-to-binder ratios, higher RSF content, and thickening application enhanced static and dynamic yield stress, extrudability, and buildability. At 0.16 water-to-binder ratio, 3% RSF volume, and 0.1% thickener concentration, the best combination was found. [86].

In order to improve mechanical qualities, interlayer bonding, and durability without sacrificing printability, MORTADA et al. have effectively reinforced 3D-printed Ca(OH)<sub>2</sub>-activated geopolymers concrete (GPC) with recycled steel fibers. Flexural strength increased 69% and tensile strength tripled to 3.75 MPa after 28 days with 1.2% SF. A crucial issue with 3D-printed concrete, the study also discovered that SF enhanced early-age toughness and minimized fracture propagation between printed layers. The study shows how recycled steel fibers may enhance the qualities of 3D-printed concrete and provides a sustainable reinforcing method for 3D printing in construction [87].

Using steel fibers as responsive elements, GUO et al. studied cement paste magnetorheology. A camera-equipped mini-slump device recorded cement paste flow under magnetic fields at varying water-to-cement ratios and steel fiber concentrations. After a short-term vertical magnetic field, cement pastes with steel fibers reduced by 0.7%-8.2%, and after a horizontal magnetic field, the flow velocity and parallel flow diameter decreased. Steel fibers migrate under a magnetic field and retain their places, causing an uneven distribution, the study found. These findings suggest active regulation of steel fiber-reinforced cement-based composites' rheology [88].

Advanced steel fibers enhance the mechanical properties of 3D printed concrete, improving tensile strength, compressive strength, and durability. Their specific shapes and volumes allow for better alignment during printing, optimizing concrete performance.

### 3.5.2 polypropylène fibers

Polypropylene fibers improve the mechanical properties of 3D printed concrete, increasing compressive strength, flexural strength, and dimensional stability, particularly with an optimal fiber length of 6 mm and a utilization ratio of 0.4%. [89] HOPKINS et al. analyze the impact of polypropylene (PP) fibers in three-dimensional printed concrete (3DPC). While PP fibers enhance form retention, rheological properties, and interlayer bonding, they can increase yield stress and viscosity, affecting extrudability. An optimal dosage of fibers improves compressive and flexural strength, but excessive amounts may lead to clustering and decreased performance. Aligned fibers can reduce shrinkage-induced cracking and affect mechanical anisotropy. The study highlights gaps in the understanding of hybrid systems and fiber orientation, advocating for standardized testing. Optimal print quality is associated with 6 mm fibers, nozzle sizes of 4 to 6 mm, and speeds of 40 to 60 mm/s [90].

Polypropylene fibres enhance the compressive strength of materials by 5–30%, flexural strength by 10–50%, and ductility and toughness by 30% to 160%. They significantly

improve crack resistance and fire resistance, retaining up to 80% of residual strength at 600°C. Additionally, polypropylene fibres increase freeze-thaw resistance by 15–40% and sulfate and chloride resistance by 20–55% [91].

XIA et al. studied how polypropylene (PP), basalt, and steel fibres (Fig 5) affect 3D printed concrete's workability, printability, rheology, and mechanical qualities. owing to greater cement paste consumption, PP fibres reduced flow spread, basalt fibres reduced it owing to water absorption, and steel fibres reduced it the most due to density and interlocking. Steel fibres had the most influence, with ideal mechanical characteristics at 0.5% PP, 0.3% basalt, and 0.7% steel. Steel fibres' stiffness and matrix interlocking increased strength best. The study also discovered that print strips had primarily vertical PP fibres [92].

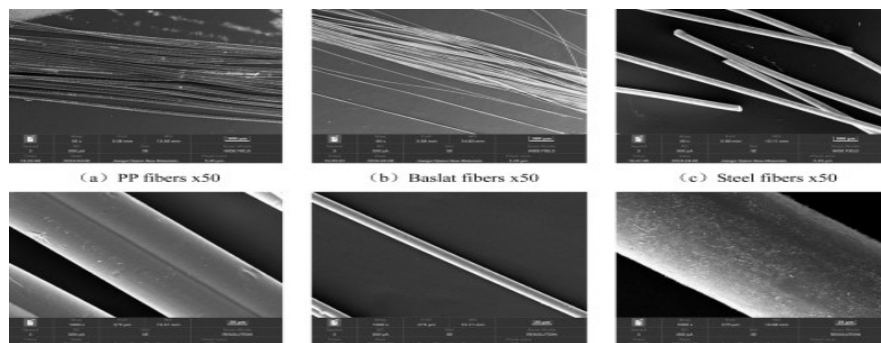


Fig 6 Micro morphology of PP fibers, basalt fibers, and steel fibers [92].

Polypropylene fibres enhance the mechanical properties of 3D printed concrete, improving strength, ductility, and durability, which makes the mix more suitable for various structural applications.

### 3.5.3 polyethylene fibers PE

All three types of embedded filament fibres—Basalt, Glass, and Polyethylene—enhanced the mechanical properties of 3D printed mortar, with Polyethylene fiber providing the most significant improvements: a 36.4% increase in flexural strength, a 29.9% increase in compressive strength, and a 36.1% improvement in interlayer bond strength. LI et al. concluded that these fibres bonded effectively with the cement mortar [93].

As formwork, LIU et al. suggested hollow 3D printed mortar (3DPM) columns reinforced with continuous PE or carbon fibres. The hollow formwork was filled with concrete to build columns to study continuous fiber reinforcement's impact on compressive strength and confinement. Compressive strength and nonlinear behavior were studied using theoretical and finite element approaches. 23.36% increased strength for 12 K carbon fibres, while 996% increased ductility for 3 K. Due to the 8.72% and 811% strength increases of three-strand and single-strand PE fibres, ductile failure occurred. These results show that continuous fiber-reinforced 3D printed concrete can increase ductility by following the production process (Fig 7) [94].

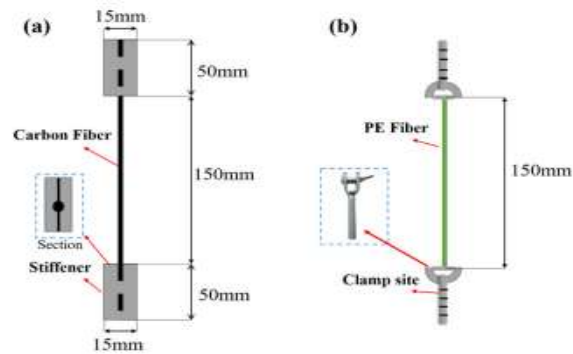


Fig 7 Fiber tensile strength test (a) carbon fiber (b) PE fiber [94].

LIU et al. demonstrated that enhancements in polyethylene (PE) fiber parameters—length, aspect ratio, and elastic modulus—significantly enhance the tensile properties of high-strength high-ductility concrete (HSHDC). Improvements in tensile strength, strain, and energy dissipation range from approximately 10.1% to 34.8%, 10.6% to 120%, and 14.1% to 186%, respectively. The optimal fiber parameters for HSHDC were determined to be a fiber length of 12 mm and a diameter of 24  $\mu\text{m}$  for compressive performance, while a length of 15 mm and diameter of 27  $\mu\text{m}$  were found optimal for tensile performance. Additionally, a mechanical constitutive model was developed that correlates well with experimental outcomes [95].

According to PHAM et al., molded specimens demonstrated superior strength compared to 3D-printed ones, with Z orientation strengths surpassing those in Y orientation. The optimal fiber content for polyethylene (PE) and high-modulus polyethylene (HPE) reinforcement in printed concrete was found to be 0.5%. The study evaluated the flexural and compressive strengths of thirty-six printed and twenty-one molded specimens, analyzing cracking patterns that highlighted differences in mechanical behavior between the two types [96].

Using 3D printing cementitious composites 3DP-ECC eliminates steel reinforcement to increase crack resistance. As a cheaper, greener quartz sand substitute, 3DP-ECC uses hybrid polyethylene and polyvinyl alcohol fibers with Yellow River Sand. RAZA et al. explore its mechanical and microstructural properties. Above 3% tensile stress, Cast and 3DP-ECC strain-harden. With 4.60% and 3.90% stresses, cast ECC has 6.58 MPa tensile strength and 3DP-ECC 4.60 MPa. Exemplars bent less in X and Y than Z. R50 castings collapse at 49.7 MPa, 3DP specimens 45.9. YRS concentration lowered 3DP-ECC porosity and interlayer gaps, although fiber-matrix bonding and hydration gels were found. The study suggests optimizing fiber alignment and interlayer bonding to strengthen 3DP-ECC [97].

Polyethylene fibers improve the mechanical properties of 3D printed concrete by enhancing compressive and flexural strengths, along with interlayer bond strength. Their incorporation compensates for the limitations of traditional 3D printing, which often excludes steel bars, resulting in a more robust and durable material for structural applications.

## 4. Conclusion

Innovation in materials for 3D concrete printing is revolutionizing the construction sector by improving productivity, offering greater architectural freedom, and enhancing durability. However, for this technology to become a reliable and widely adopted standard, it is essential to continue research on several critical aspects such as interlayer strength, durability, material reinforcement, mixture stabilization, and process standardization. Addressing these technical and scientific challenges is crucial to enable 3D concrete printing to evolve from an emerging technology to a fully mastered and sustainable solution for the future of buildings. This transition could transform not only construction methods but also the standards that underpin the modern construction industry.

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