TECHNICAL ADVANCEMENTS IN 3D CONCRETE PRINTING FOCUSING ON SUSTAINABLE OBJECTIVES WITH EMPHASIS ON CONCRETE MIX DESIGNS, PROPERTIES, AND TESTING METHODOLOGIES

1. Introduction

The emergence of 3D concrete printing (3DCP) represents a significant advancement in construction technology, offering opportunities to revolutionize traditional building methods. Initially rooted in digital construction, 3DCP has garnered global attention for its capacity to address critical industry challenges, including waste reduction, enhanced site safety, and the realization of complex design within accelerated construction schedules [1, 2]. Unlike conventional methods reliant on manual labor, 3DCP utilizes digital fabrication to extrude concrete layer by layer with enhanced precision, thereby allowing the creation of complex architectural forms [3].

This technology has also proven its alignment with sustainability objectives by repurposing construction waste into secondary materials and reducing dependence on natural resources, rendering it a viable option for the construction sector. Some of the noteworthy examples include a military shelter made in 36 hours, a double-story house, and the world's longest 3D-printed pedestrian bridge, as recognized by the Guinness Book of Records [4]. Projects such as the circular housing prototype TECLA in Massa Lombarda (Ravenna, Italy) further demonstrate the technology's versatility, employing multiple synchronized 3D printers to work simultaneously and utilizing raw earth as a fully natural, recyclable, and carbon-neutral material [5, 6].

However, the effectiveness of 3DCP relies on optimizing material parameters, such as composition and rheological properties, to ensure the structural integrity and durability of printed elements while minimizing waste [7]. Despite its potential, widespread adoption of 3DCP is contingent upon overcoming various technical challenges, including the refinement of concrete mixtures to meet the rigorous demands of the printing process and ensuring the load-bearing capacity of printed structures [8, 9]. This literature review aims to explore recent advancements, challenges, and prospects of 3DCP technology, with a focus on material aspects such as concrete mix designs, properties, and testing methodologies. By examining research and industry developments, this review seeks to drive further innovation in 3DCP, promoting sustainable and efficient building practices.

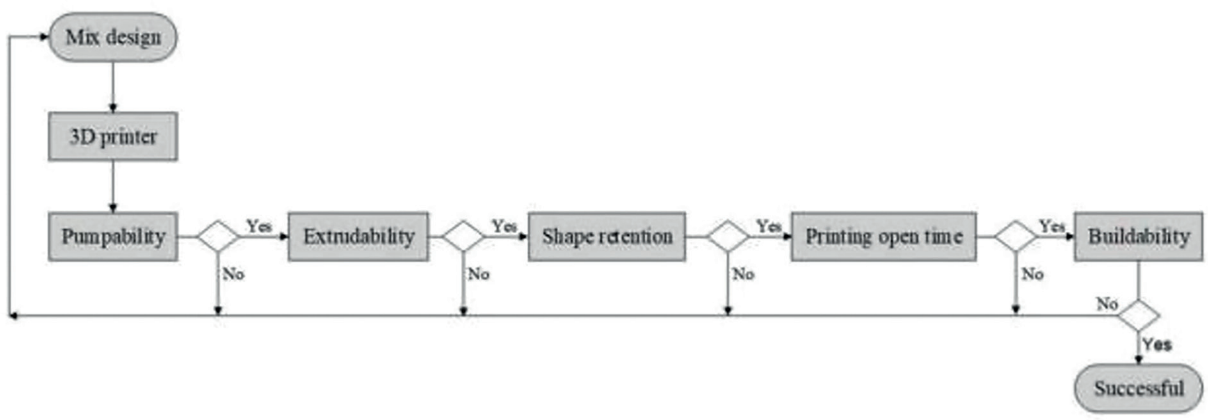

Figure 1. Iterative process of preparing a printable concrete mix [12].

2. Types of Concrete for 3D Printing

2.1. Traditional concrete mixes

Traditional concrete mixes, comprising Ordinary Portland Cement (OPC) as the binder material, have long been fundamental to construction worldwide. However, utilization of OPC comes with a significant environmental cost. Its production contributed substantially to global anthropogenic CO_2 emissions, accounting for approximately 5-7% of the total world carbon emissions [10]. This emission arises primarily from two key processes: the calcination of limestone, a crucial ingredient in OPC, leading to CO_2 release, and the high energy consumption during manufacturing [11].

Despite its historical efficiency, OPC-based mixes may not align well with the demands of 3D printing applications due to inherent limitations. Their rheological characteristics often fall short of meeting the specific requirements of 3DCP processes, such as pumping, extrusion, and buildability [12]. Moreover, traditional mixes may struggle with pumpability due to viscosity and setting times, resulting in issues like phase segregation and poor cohesion. Similarly, poor extrudability can lead to discontinuous filaments or distortion under self-weight during extrusion. Their slow strength and stiffness development may impede buildability, compromising the ability to support successive layers without deformation. Thus, while traditional concrete mixes have been prevalent in construction, their limitations highlight the necessity for optimized mixtures tailored to the unique demands of 3DCP.

2.2. Specialized concrete mixes

To address the challenges mentioned in the previous section and fully leverage the potential of 3DCP technology, researchers and industry experts are actively developing concrete formulations specifically optimized for this purpose. These optimized mixtures aim to exhibit enhanced rheological properties, ensuring smooth extrusion and robust layer adhesion, while also maintaining adequate strength development to uphold the structural integrity of printed elements.

A critical consideration is the presence of coarse aggregate (CA), which presents challenges during pumping and extrusion [12]. To facilitate pumping, traditional mixes require a lubricating layer, yet in printable mixes, minimal lubrication can lead to pipe blockages and nozzle clogs due to the absence of CA. Specialized mixes address this by substituting CA with finer particles like binders, fillers, and fine aggregates. However, increasing fine content may heighten susceptibility to shrinkage cracks and raise environmental concerns from excess cement usage. Ongoing research aims to explore higher aggregate-binder ratios and adapt printing equipment to accommodate CA, mitigating shrinkage and sustainability issues. By reducing the reliance on cementitious materials and optimizing the mix design, the environmental impact associated with excess cement usage can be minimized.

Considerations are extended to the compatibility of a concrete mix with the printing process, which is evaluated step by step, considering pumping, extrusion, shape retention, open time, and buildability, as illustrated in Figure 1. This assessment ensures that the mix meets the specific requirements of each stage of the printing process, thereby enhancing efficiency, quality, and sustainability practices.

3. Concrete Properties and Testing

Understanding the properties of concrete is essential for research in the field of 3DCP. These properties are categorized into two main types: fresh properties and hardened properties.

Fresh properties include characteristics such as pumpability, extrudability, and buildability, which influence how easily concrete can be printed and shaped during the printing process. On the other hand, hardened properties, including compressive strength, flexural strength, and durability, evaluate the strength and resilience of concrete after it has cured.

3.1. Fresh properties

3.1.1. Pumpability

In 3DCP, pumpability is crucial for smoothly transporting the material through a pumping system to the printing nozzle with uniform consistency [13]. It dictates how effectively the concrete mixture can be delivered to the desired printing location, which is an important factor for precise layer-by-layer deposition in 3DCP.

Pumpability significantly impacts various aspects of the printing process, including surface quality, flow consistency, and overall printability. A concrete mixture with good pumpability ensures smooth material flow through the printing system, enabling accurate extrusion and deposition of each layer. Conversely, poor pumpability can lead to issues like uneven flow, blockages, or inconsistent layer deposition, compromising print quality and structural integrity.

3.1.2. Extrudability

Another fundamental aspect of 3DCP is extrudability, which defines the material's ability to be consistently and effectively extruded through the printing nozzle while maintaining proper flow, cohesion, and dimensional accuracy throughout the printing process [14]. A concrete mixture with excellent extrudability flows effortlessly through the printing system, allowing for precise control over the deposition process without clogging or uneven distribution [15].

However, having the right balance in rheological properties is also as important to avoid issues such as sagging or uncontrollable flow as the concrete mixture may flow unevenly or excessively, leading to deformities in the printed layers or even structural failure. To achieve optimal extrudability, factors to consider include mix proportion parameters such as water-binder ratio, aggregate-binder ratio, aggregate characteristics, and chemical admixture dosage.

3.1.3. Shape Retention

Shape retention refers to the concrete mixture's ability to retain the desired shape and structural integrity once it has been extruded from the printing nozzle. Creating complex architectural elements such as curved walls, customized facades, and intricate ornamentation relies on this aspect [16].

Achieving effective shape retention requires great attention to the printability of the concrete mixture. Printability involves ensuring precise flow characteristics for accurate layer deposition and complex geometry fabrication. A key consideration in printability is striking a balance between maintaining a prolonged dormant time for pumpability and ensuring immediate stiffening for buildability. This balance is often achieved through the strategic use of retarders and accelerators, which regulate the concrete's setting time and viscosity to optimize both flowability and structural integrity during printing.

The workability of the concrete mixture also significantly influences shape retention in 3DCP. A mix with good workability allows for smooth extrusion through the printing nozzle and accurate shaping of the printed layers. On the other hand, poor workability can result in issues such as nozzle clogging or inconsistent layer deposition, affecting the quality and stability of the printed structure.

3.1.4. Setting time

In terms of construction scheduling and project timelines, there is a greater focus on setting time, which refers to the duration needed for concrete to set and harden after mixing [17]. It directly impacts the efficiency of construction operations and influences the overall pace of the project. To enhance flexibility in scheduling and sequencing, advanced mix designs often incorporate additives or supplementary cementitious materials to adjust setting time. However, finding the optimal setting time is essential. Rapid setting may hinder smooth flow through the nozzle or proper adhesion to previous layers, while prolonged setting time can lead to printing delays and increase the risk of layer deformation or collapse before setting.

Table 1. 28-day compressive strength test results and the coefficient of variance (CoV) of the specimens [19].

	Direction 2		Direction 3	
Mix	Strength (MPa)	CoV (%)	Strength (MPa)	CoV (%)
50FA10SF	31.1	4.3	36.3	1.0
40FA20MK$_{60}$	37.9	7.1	38.6	8.1
60GGBS	43.1	3.3	55.5	5.3

3.2. Hardened properties

3.2.1. Mechanical properties

Understanding the mechanical properties of hardened concrete is important for assessing its strength and structural integrity, particularly in the context of 3DCP. These properties serve as fundamental indicators of its performance under various stresses, guiding the optimization of printing parameters and material formulations.

Compressive strength is a key mechanical property determined by subjecting concrete specimens to axial loads. It provides a primary measure of concrete's load-bearing capacity, directly influencing the stability and durability of 3DCP structures [18]. Another property is tensile strength, which reflects the concrete's resistance to being pulled apart. This property is particularly important in tension-dominated situations commonly encountered in 3DCP applications such as bridges, cantilevered structures, and facades. Lastly, flexural strength evaluates the capacity of concrete to endure bending or flexural stresses, essential for assessing the performance of 3D printed beams, slabs, and other structural elements.

3.2.2. Durability

Durability in 3DCP is key in ensuring the long-term performance of printed structures in demanding real-world environments. It refers to the ability of concrete to withstand various external factors and environmental conditions over an extended period without significant deterioration. This includes resisting degradation from factors such as weathering, chemical exposure, mechanical stresses, and biological agents [19].

However, the durability behavior of 3D-printed concrete would be different from conventional concrete due to the use of different mix proportions, high dosage of chemical admixtures, and layer-by-layer construction methods. As 3DCP involves layer-by-layer deposition of concrete, the durability of printed components is influenced by several factors unique to the printing process. These include the selection of printing materials, such as binders, aggregates, and admixtures, as well as the optimization of printing parameters like layer thickness, printing speed, and nozzle size [7].

Another challenge in ensuring durability is to tailor the material composition and printing parameters to withstand the specific stresses and environmental conditions encountered during construction and throughout the service life of the structure. To enhance durability, researchers focus on developing concrete mixtures with improved resistance. This may involve incorporating specialized additives, such as corrosion inhibitors, waterproofing agents, or fiber reinforcements. Additionally, optimizing printing parameters to ensure proper bonding between layers, adequate compaction, and uniform distribution of materials can contribute to the overall durability of printed structures. Figure 2 illustrates these main influential parameters that define the durability behavior of printed concrete.

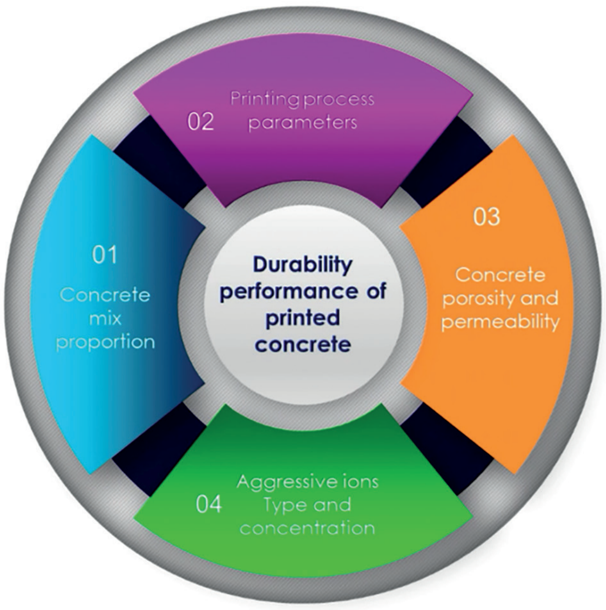

Figure 2. Parameters influencing the durability performance of 3D-printed concrete [7].

3.2.3. Dimensional stability

Dimensional stability pertains to the ability of concrete to maintain its shape and size over time [20]. Shrinkage, induced by moisture loss or chemical reactions, poses a significant concern as it can result in cracking and deformation if not adequately managed. Additionally, creep, the gradual deformation of concrete under sustained load, can adversely affect the long-term behavior and serviceability of printed structures. Proper control and management of these factors are essential to mitigate potential issues and ensure the durability and stability of concrete structures.

4. Concrete Mix Design

4.1. Advances on components of concrete mix

4.1.1. Primary components

Traditional concrete formulations, which heavily rely on high volumes of ordinary Portland cement (OPC), contribute to approximately 10% of global CO_2 emissions [21]. To address this challenge, researchers have investigated alternative binders such as fly ash (FA), silica fume (SF), slag (GGBS), and metakaolin (MK60), aiming to reduce OPC content and enhance sustainability. For instance, Colyn et al. devised mixtures with an increased aggregate-to-binder mass ratio from 1.6 to 1.75 to minimize clinker usage and enhance stiffness. These mixtures exhibit high thixotropy, meeting critical rheological requirements for 3D printing, with 28-day compressive strengths ranging between 31 and 55 MPa and elastic modulus of 29-37 GPa as shown in Table 1 [22]. Objects printed with these mixtures demonstrate smooth, uniform surface finishes and sound buildability, fulfilling pumpability, extrudability, and buildability requirements. However, the buildability prediction model underestimates the buildability of some mixtures, indicating areas for improvement. While the feasibility of these alternative binder concrete mixes is demonstrated, further mechanical characterization, including tensile strength and interlayer region strength, as well as porosity quantification and microscopic analysis, is necessary to fully evaluate their constructability and performance in 3D printing applications.

Binders are crucial components in 3DCP, acting as adhesives that bind aggregate particles together to form solid structures. Christ et al. explored the use of binders such as mammal gelatin (MG) and κ-carrageenan to enhance bonding between particles, thereby improving strength and durability. Rheological assessments revealed optimal solution concentrations of 80-120% w/v MG and 3% w/v κ-carrageenan at temperatures of 50°C and 65°C, respectively, resulting in significant yield stress increases from 0.1 to 107 kPa upon cooling to 20°C [23]. These findings indicate superior performance compared to conventional cementitious materials. Fine-tuning of material properties, facilitated by control over solution concentrations, enhances printability and structural stability. Furthermore, using MG, sourced from waste products, offers economic and environmental benefits as a cheaper and more climate-friendly alternative to traditional cementitious mixtures. By reducing reliance on cement, this approach can lower construction costs and decrease carbon emissions. Additionally, the study demonstrates the viability of these hydrogels for 3DCP filaments, with MG-based composites exhibiting superior printability. Representative printing samples illustrated in Figure 3 show that MG composites generally exhibit better printability results, with minimal segregation compared to low concentrations of κ-carrageenan. This innovation could lead to faster build rates, higher form stability, and greater design flexibility, ultimately enabling more efficient and sustainable construction practices.

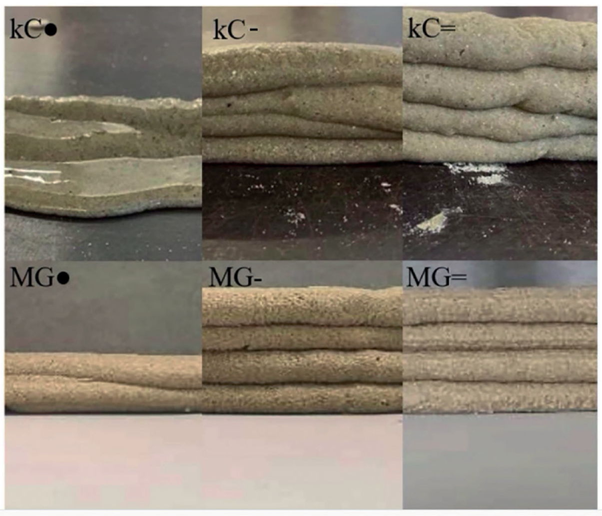

Figure 3. The classification of printability tests for the kC- and MG composites. The MG composites show the best printability [20].

4.1.2. Alternative materials and fillers

In the study by Chen et al., metakaolin, a pozzolanic material, is introduced into the concrete mixture to enhance its thixotropic behavior. Thixotropy, defined as the property of materials to become less viscous under stress, allows for improved flow and workability during processing while retaining structural integrity upon stress removal [24]. Metakaolin integration facilitates the development of a more stable microstructure, enhancing adhesion between particles, and improving overall strength and durability. It boosts the static yield stress of the concrete paste by up to 20%, indicating increased resistance to deformation, and enhances dynamic rheological properties, with the dynamic yield stress increasing from 303 to 386 Pa and the consistency factor rising from 39 to 59 [25]. Additionally, metakaolin significantly improves concrete thixotropy, reducing structure deformation from 7.69% to 4.87% during the 3D printing process.

As researchers explore novel materials to enhance concrete properties for 3D printing, geopolymer compositions have emerged as promising alternatives to traditional cementitious materials. Over the past decade, substantial research has explored the productivity and properties of 3D printed geopolymers, emphasizing their rheological, physical, and mechanical characteristics. Geopolymers, introduced in the 1970s, offer a low-carbon and environmentally friendly alternative to traditional cementitious materials [26]. Compared to ordinary concrete, geopolymers can reduce CO_2 emissions by up to 45% [27], while also exhibiting superior properties such as faster hardening, higher temperature resistance, excellent corrosion resistance, and durability.

Further advancements in geopolymer research focus on optimizing binder compositions and enhancing mechanical properties for 3D printing applications. Jaji et al. concentrate on enhancing metakaolin-based binders with slag for 3D printed geopolymer concrete (3DPGPC) applications. By incorporating slag up to 30% at 10% intervals and increasing the aggregate-to-binder ratio to 2, mechanical performance and microstructural properties of 3DPGPC are improved [28]. The addition of 3% sodium phosphate retarder enables sufficient open time for constructability. While the study demonstrates improved mechanical properties and microstructural characteristics, potential drawbacks such as decreased workability with higher slag contents should be considered for practical applications in 3DCP.

Additionally, exploration of unconventional additives like mineral wool presents new avenues for enhancing concrete properties and performance in 3D printing. In a novel approach, Pavlin et al. investigate the feasibility of incorporating mineral wool into alkali-activated mixtures for 3D printing applications. By integrating mineral wool along with co-binders like bottom ash, calcium aluminate cement, and microsilica, the mixture's composition is optimized for 3D printing. The study demonstrates compressive strengths exceeding 50 MPa after 28 days of curing and thermal stability up to 700°C [29]. Notably, 3D-printed samples exhibit less shrinkage and expansion compared to molded samples due to their artificial porosity. Despite potential drawbacks such as increased porosity affecting mechanical strength, the study offers valuable insights into the suitability of the developed mixtures for 3DCP.

Table 2. Analysis of multi-way ANOVA and multiple regression analyses for structural build-up coefficient of U3DCP [31].

Variation	Sum of square	Mean square	F-value	P-value	Regression coefficients *r*
HEC**	19,100.46	6366.82	34.34	0.001	1729.23
WLG**	5329.26	1776.42	20.74	0.003	935.96
W/C*	2685.19	1342.60	7.24	0.033	-658.06
FN	589.76	294.88	2.71	0.145	-7.19
SP	2126.21	1063.10	4.83	0.056	-117.33

4.1.3. Additives and modifiers

Zavaleta et al. explore the integration of chitosan and sisal fibers as natural additives in earthen-based composites for 3D printing applications, offering an eco-friendly alternative to ordinary cement-based formulations. Chitosan, derived from the shells of crustaceans, is a biopolymer known for its antimicrobial properties and biodegradability. On the other hand, sisal fibers, extracted from the leaves of the Agave sisalana plant, are renowned for their strength and durability.

By incorporating a 3.0% (w/v) aqueous chitosan solution and 1.0% (w/w) sisal fibers, the mechanical strength and water durability of the composites are significantly enhanced [30]. The chitosan solution improves compressive strength and water resistance. The optimized ratio of chitosan solution to solid contents (29:71) is suitable for printing, resulting in enhanced mechanical resistance and water durability. However, the presence of chitosan prolongs the drying process, warranting further investigation into the hardening process.

While advancements in terrestrial 3DCP are substantial, exploration of underwater construction, known as underwater 3D concrete printing (U3DCP), remains nascent. Wang et al. investigate the fresh-state buildability and interlayer bonding of concrete printed underwater compared to air-printed concrete [31]. Researchers identify factors influencing the structural build-up coefficient, with hydroxyethyl cellulose (HEC) and wilan gum (WLG) exhibiting significant impact. Multi-factor ANOVA and regression analyses reveal their order of importance (HEC > WLG > W/C ratio > SP > fineness module (FN)) as shown in Table 2, facilitating optimization of ingredient proportions to enhance buildability and reduce water permeability. Predictive formulas for printable heights show a correlation coefficient of 0.85 for underwater printing. Additionally, weakened interlayer adhesion underwater, 20.4% less than in air-printed specimens, is highlighted, with variations influenced by time intervals and concrete composition.

On the other hand, nanoclay and high-range water-reducing admixtures (HRWR) emerge as promising additives for improving 3D printing mixes. In another study, Moeini et al. identify nanoclay and HRWR as suitable additives for developing 3D printing mixes. Through rheometric tests, the addition of nanoclay increases the thixotropic index, particularly in the presence of HRWR [32]. A higher thixotropic index suggests enhanced fluidity, improving the material's ability to maintain shape and form stable layers during deposition, thereby enhancing print quality and structural integrity [33]. However, a balance between rigidity and fluidity is necessary for stability and extrudability, with a minimum static yield stress of 200 Pa deemed necessary for single-layer stability.

Sustainable construction practices drive exploration into alternative materials like ultrafine glass powder (UFGP) for enhancing concrete performance. Zhou et al. investigate the integration of UFGP into reactive powder concrete (RPC) for 3DCP applications, aiming to enhance performance, durability, and environmental sustainability [34]. Results indicate that incorporating 25% UFGP increases slump flow by 27.45%, demonstrating improved workability. A 20% UFGP dosage also shows minimal reduction in compressive and flexural strength, making it a viable option for maintaining structural integrity. Additionally, the use of UFGP reduces carbon emissions by 23.77%, contributing to environmental conservation.

4.1.4. Advanced cementitious materials

In furthering the capabilities of 3DCP, emphasis is placed on addressing challenges related to rheology control and sustainability. Chen et al. developed limestone-calcined clay-based cementitious materials activated with $Ca(NO_3)_2$ solution, as outlined in Table 3, for sustainable and set-on-demand 3D printing using an inline static mixer-based setup. Pumpable mixtures, comprising cementitious materials (CM) and acceleration slurries (AS), were formulated and mixed to create a final printable mixture with a low OPC content of about 275 kg/m^3 [35]. This mixture exhibited commendable buildability performance and a 28-day compressive strength exceeding 30 MPa. The addition of $Ca(NO_3)_2$ solution improved initial setting time, buildability, and structural build-up. However, it may also reduce flowability and increase dynamic yield stress, posing challenges in formulation.

Table 3. Mix designs of cementitious materials and acceleration slurries [35].

Cementitious material	Portland cement	Limestone powder	Calcined clay	Water	Aggregate	Superplasticizer (wt.% of the binder)
CM-0.5	0.55	0.15	0.30	0.30	1	0.5
CM-0.6	0.55	0.15	0.30	0.30	1	0.6
CM-0.8	0.55	0.15	0.30	0.30	1	0.8
CM-1	0.55	0.15	0.30	0.30	1	1
Acceleration slurry		**Limestone powder**		**Water**	**Aggregate**	**$Ca(NO_3)_2$ solution* (wt.% of limestone powder in acceleration slurry)**
AS-0		1		0.30	1	0
AS-7		1		0.26	1	7
AS-14		1		0.22	1	14

$Ca(NO_3)_2$ solution: 50wt% of $Ca(NO_3)_2$.*

6. Conclusion

This review highlights significant progress in the field of 3D concrete printing (3DCP), showcasing advancements aimed at enhancing the performance, durability, and sustainability of concrete structures. A discernible trend is the exploration of alternative binders and additives to improve 3D printed concrete properties. Studies have shown the effectiveness of incorporating materials like nanoclay, metakaolin, and slag, resulting in improved rheological properties, buildability, and mechanical strength.

Looking ahead, future research in 3DCP is set to revolutionize construction practices by leveraging innovative concrete mix designs. Emerging trends suggest a continued focus on optimizing materials and processes to enhance efficiency, reduce environmental impact, and broaden the application scope of 3D printing in construction. By embracing sustainable practices and fostering collaboration, 3DCP offers faster, more efficient, and eco-friendly solutions for constructing complex structures.

In summary, the collective efforts in advancing 3DCP have shown its potential as a transformative technology in the construction industry. As research progresses and boundaries are pushed, the vision of a more sustainable and resilient built environment driven by 3D printing technology draws closer to reality.

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