buildings

Review

Advancement in Sustainable 3D Concrete Printing: A Review on Materials, Challenges, and Current Progress in Australia

Kumari Gamage [1], Sabrina Fawzia [2], Tatheer Zahra [2], Muge Belek Fialho Teixeira [3] and Nor Hafizah Ramli Sulong [2,*]

[1] Department of Civil Engineering, University of Moratuwa, Moratuwa 10400, Sri Lanka; kgamage@uom.lk
[2] Group of Sustainable Engineered Construction Materials, School of Civil & Environmental Engineering, Faculty of Engineering, Queensland University of Technology, 2 George St., Brisbane, QLD 4000, Australia; sabrina.fawzia@qut.edu.au (S.F.); t.zahra@qut.edu.au (T.Z.)
[3] School of Architecture and Built Environment, Faculty of Engineering, Queensland University of Technology, 2 George St., Brisbane, QLD 4000, Australia; muge.teixeira@qut.edu.au
* Correspondence: hafizah.ramlisulong@qut.edu.au; Tel.: +61-731384476

Abstract: Three-dimensional concrete printing (3DCP) is a sustainable and green approach for rapid construction with the ability to create complex shapes to preserve the intended aesthetic appearance for an affordable cost. Even after a decade of attempts, there are many limitations and challenges to applying this technology for constructions without borders. The lack of guidelines for mix designs, quality control procedures during extrusion, printing and building phases, compatibility of material with extruder, standard testing, and guidelines to verify suitability of mixture with respect to the application and exposure conditions and limited machine capacity are several areas to be addressed for applications without borders. The development of 3DCP applications as a sustainable and green technology is another challenging task due to high Portland cement consumption in 3DCP. However, reducing the high usage of ordinary Portland cement (OPC) with pozzolanic waste materials replacement and environmentally friendly cement indicates the direction of moving 3DCP into a sustainable pathway. The authors reviewed more than 200 refereed articles published on materials and techniques in 3DCP. Inconsistency in disseminating knowledge in research articles has hindered the creation of a monolithically connected chain of research efforts and findings in accelerating the development and adoption of this technology. This paper summarizes the common approach to developing 3DCP mix designs and identifies the key areas for the future development of materials and techniques and challenges to be addressed for the global adoption of 3DCP. The current progress and challenges in the context of Australia's construction industry and future trends for the acceptance of 3DCP are also reviewed.

Keywords: 3D concrete printing (3DCP); 3DCP in Australia; extrusion-based printing; mix design; waste materials; interface failure; shape retention

check for updates

Citation: Gamage, K.; Fawzia, S.; Zahra, T.; Teixeira, M.B.F.; Ramli Sulong, N.H. Advancement in Sustainable 3D Concrete Printing: A Review on Materials, Challenges, and Current Progress in Australia. *Buildings* **2024**, *14*, 494. https://doi.org/10.3390/buildings14020494

Academic Editor: Elena Ferretti

Received: 29 December 2023
Revised: 25 January 2024
Accepted: 5 February 2024
Published: 10 February 2024

1. Introduction

Additive printing technology has been introduced to the construction industry, expecting fast, reliable, and cost-effective constructions, while providing opportunities to print complex shapes with improved appearance. This concept was first presented in 1997 [1] and later researchers in the United Kingdom developed a digital structural model in 2005 by depositing layers of fresh concrete [2]. Researchers and practitioners in all parts of the world have been attempting to fully adopt this construction method for a wide range of applications by overcoming the current weaknesses and improving the strengths and adaptability [3,4]. This technology has been proven to reduce construction costs and increase productivity, with additional benefits such as reduced carbon emissions and waste, design freedom, and greater precision.

Binder jetting, layered material extrusion and robotic shotcrete have currently been used in 3D concrete printing (3DCP) technology [5,6]. Extrusion-based 3DCP technology is more favorable than the powder-based technique. This is mainly due to the ease of application and suitability of adoption for large-scale monolithic constructions [7–10]. This involves extruding materials through nozzles mounted on a gantry system, robotic arm, or crane [11–13]. The standard and stability of printed material or object depend on the printer properties such as size, geometry, operating mechanism, printing head details, nozzle size, shape, and speed; thixotropic and rheological properties of the material; printing pressure; filament parameters (number, width, and height of filaments); environmental conditions (humidity, temperature, etc.) [14–16].

According to the authors' knowledge, most researchers have presented the outcomes of trials on mix designs focusing only on the fresh and hardened properties of either materials or both materials and printed objects. The effectiveness of the mix design may vary from country to country depending on the printer parameters and climatic conditions such as environmental temperature and humidity. Hence, it is important to state all indirect parameters, including environmental temperature, humidity, and printer properties, in addition to a detailed process of mix designs and development when disseminating research outcomes. The authors examined the content of 194 recent publications from 2018 to 2023, filtered under 3DCP, and the inclusion of important facts was analyzed as illustrated in the Venn diagram (Figure 1). This clearly indicates the lack of important parameters stated in publications that are required for the consistent development of materials and techniques to avoid inconsistency in construction applications.

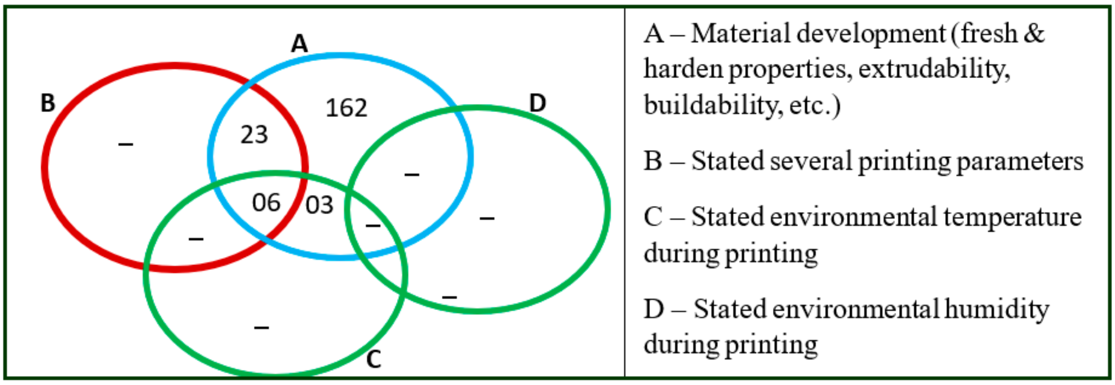


Figure 1. Integration of key details of 3DCP based on 194 journal articles.

Advanced research on 3DCP has increased exponentially in the last decade. However, there are still many limitations in applying this technology into practice in many parts of the world. Several countries (Australia, China, United States and Europe) have successfully applied this technology for single or two-storey buildings. The majority of all industry players are facing the same challenges in expanding this technology towards high-rise buildings and load-bearing infrastructures. Hence, it is imperative to identify the critical limitations of the current research, particularly on the sustainability aspect of 3DCP. This paper summarizes existing research outcomes on fresh and hardened properties of 3DCP with alternative supplementary materials, the identified drawbacks, their nature, and the authors' view on developing this technology towards a successful green approach, as shown in Figure 2, to eliminate the gaps between existing knowledge and development approaches.

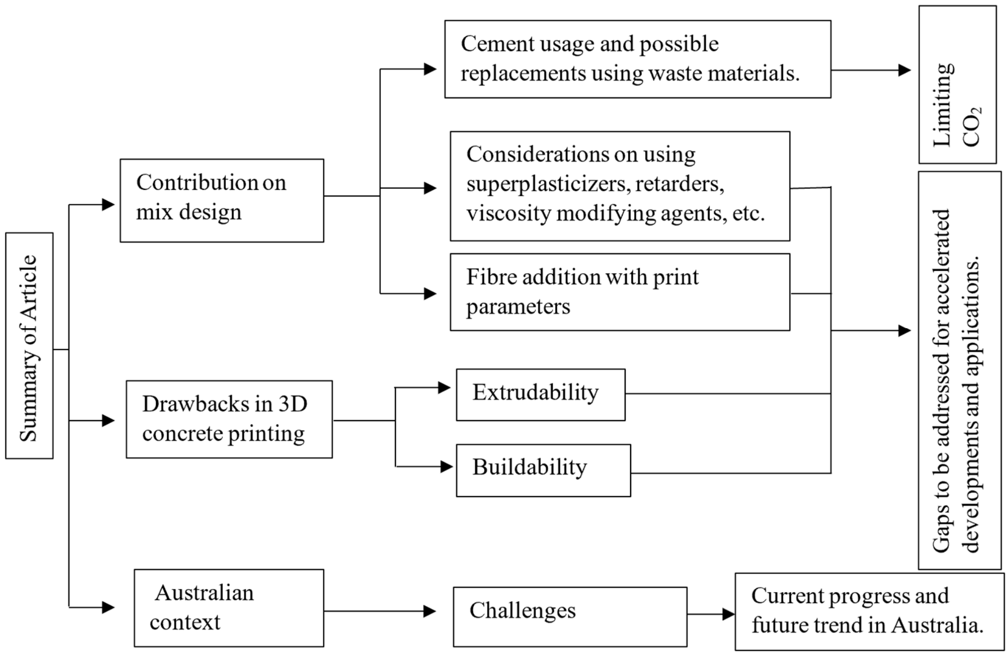


Figure 2. Overview and highlights of the article.

With a broad scope, researchers have been attempting to develop sustainable mixtures with varying constituent materials and their proportions to drive this technology into a green and sustainable direction [17,18]. Even though excellent outcomes are presented in these published articles, some critical aspects are not stated to guide future researchers in this development. This article is structured to direct future researchers with a broad understanding of additive printing constructions and provide guidance to include all essential data for developing standards and design guidelines.

This paper identifies the drawbacks to be addressed in the different phases of 3DCP mix design development, their root causes and successful approaches. Since almost all researchers have been focused on developing a single phase or a property, innovative development approaches to achieving a structurally sound element have been hindered. This study discusses the overall picture concerning the development of 3DCP together with possible alternative materials and techniques. The summarized key findings and contributions lay a sound foundation to identify future research needs and alternative channels to develop this technology in a sustainable and green manner.

2. Mix Designs, Constituent Materials and Considerations

The accelerated development of 3DCP in the past ten years has shown the potential to revolutionize the construction industry in the future decades. Investigations on mix designs based on structural strength requirements and durability and categorization of data based on the nature of intended usage and life expectancy of the structure are essential to achieve remarkable applications. The development of standards for mix designs and structural designs based on failure criteria with the specifications for durability and quality control in construction are also deemed important. This section summarizes successful approaches of mix designs, cement usage and possible replacements of waste materials to minimize environmental effects resulting from high usage of ordinary Portland cement.

A proper 3DCP mix design can be defined as designing the mixture that facilitates workability for transporting and extrusion, proper extrudability without laminate failure, uniform buildability without shape distortion and achieving the required mechanical strength and durability of the printed member. In addition, maintaining printing parameters related to extruder (nozzle diameter and filament width), process (temperatures and speed of printing), and structure (layer thickness and infill geometry) is another challenging task [19]. The performance of printed structure depends on the efficiency of maintaining the process of all latter conditions. In general, 3DCP mixture contains binders, admixtures, fine aggregates, and fibers. The performance of composite concrete mix depends on the constituent materials, proportions, strength, and their bond mechanism in the concrete matrix. Hence, it is crucial to identify the critical roles of each material in the concrete matrix on its fresh and hardened properties, as illustrated in Figure 3.

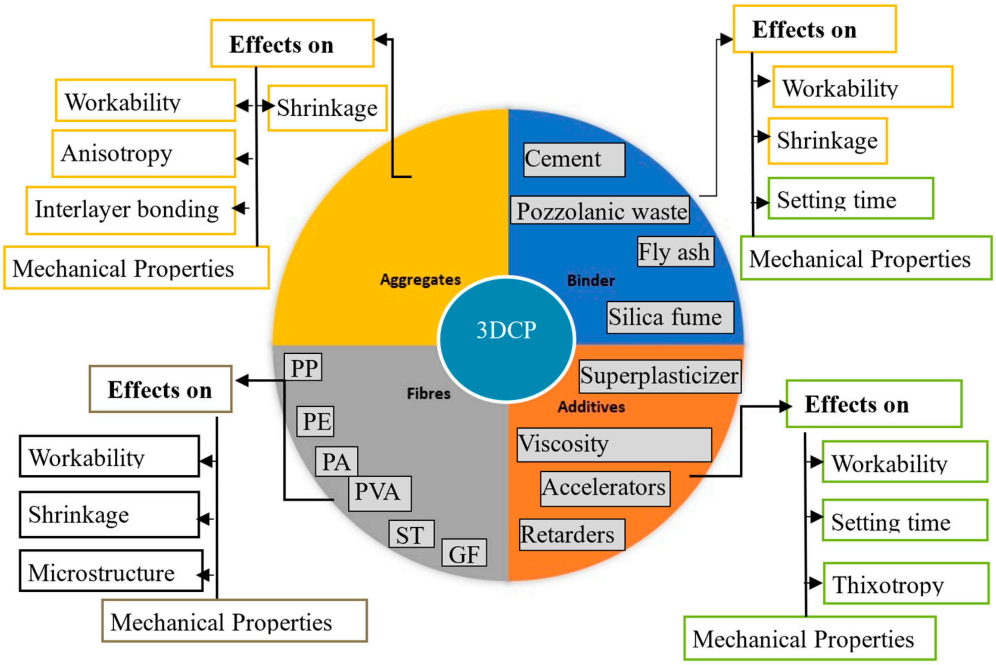


Figure 3. Constituent materials and their critical effects on end properties.

2.1. Alternative Binders and Supplementary Cementitious Materials for 3DCP

The cementitious material used in additive printing should be able to provide a mixture of required fluidity and flowability for continuous flow and effective extrusion from the nozzle, setting times to maintain desired open printing time, develop good bond strength between layers after extrusion, sufficient early strength to eliminate the possibility of deformation and able to retain the shape while placing new layers on top of it [20]. Portland cement-based concrete is weak in rapid setting, which is required for efficient 3DCP. The cementitious binder should have high workability for smooth extrusion and early strength gain for better buildability [4]. When the cement content is high, heat of hydration affects the performance of 3DCP due to an increase in the drying shrinkage, which is a critical problem in 3DCP with the absence of formwork [21]. In addition, considerably higher cement content in 3DCP mixture contributes to greenhouse gas emissions, which has adverse effects on the environment [22,23]. Hence, controlling Portland cement content in 3DCP is a timely need. However, the use of lower cement content resulted in low early strength, a longer setting time, and formation of cracks [22,23]. Mineral admixtures and fibers can be applied to overcome such issues. The addition of fly ash and silica fume can improve extrudability and buildability in 3DCP [23]. Research studies focusing on logical approaches for developing mixtures respective to the required strength grade/s, which can address all possible failure criteria based on the application, are essential. Figure 4 illustrates the optimal directions for the decision-making process, identified in this paper after a comprehensive review of published articles.

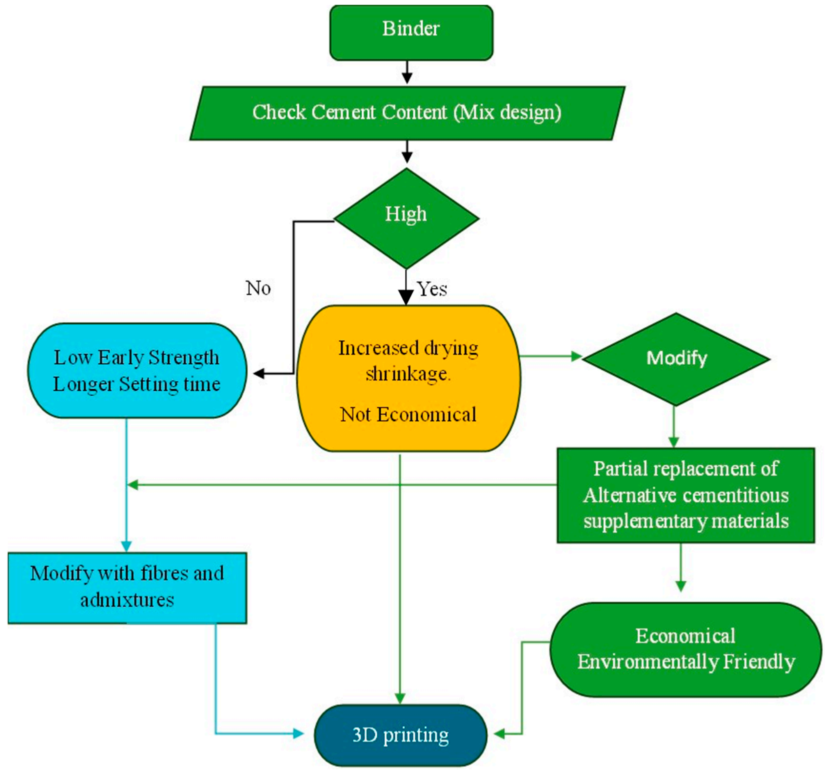


Figure 4. Illustration on decision-making pathways for the selection of binder for 3DCP.

3DCP leads to sustainable building construction by reducing waste and the use of recycled materials [24–26]. However, high cement content in 3DCP negatively affects the environment. Attempts to partially replace cement using pozzolanic waste or supplementary materials have increased in recent years [27–31]. These materials can be successfully used to partially replace the cement content in 3DCP, which helps to reduce greenhouse gas emissions to the environment and enhances the mechanical and durability properties of the printed member [27,28,32–34].

Porosity, pore shape, pore size, and pore direction affect the elastic modulus and compressive strength of concrete, which is one of the main reasons for the anisotropic feature of 3DCP [35]. The pores of the concrete casting specimens appear approximately spherical, while those in 3DCP exhibit irregular shapes in 3D space. After 28 days of curing, the total porosity of conventional concrete and 3DCP was 1.52% and 2.66%, respectively [35]. The addition of cementitious replacement may reduce the porosity due to filling effects, resulting in high durability and strength of printed members.

The waste materials such as fly ash (FA), ground granulated blast furnace slag (GGBS), silica fume (SF), and metakaolin (MK) are pozzolanic materials because they contain reactive amorphous silica and oxides [36–39]. Other pozzolanic waste materials, limestone powder (LP) as filler, rice husk ash (RHA), sugarcane bagasse ash (SCBA), and sewage sludge ash (SSA) can also be used as alternative supplementary materials for cement in 3D printing. Several successful investigations focused on controlling cement usage by applying waste materials or supplements are described below.

1. Limestone calcined clay cement (LC3):
   Large cement consumption of 3DCP is a major environmental concern. LC3 is a low-carbon alternative. CO_2 emissions in the manufacturing process of LC3 cement are low due to reduced usage of clinker, replaced with calcined clays and limestone. Limestone calcined clay cements have the potential to reduce environmental impact and, hence, can be used as an alternative to Portland cement (PC) [40,41]. Strong buildability can be attained with high LC3 content, but weak flowability and extrudability [41,42]. LC3 led to higher yield stress (1.2–2.5 times) and viscosity (+14 to +59%) with the addition of a superplasticizer. However, hydrating LC3 mixtures required higher free water content to reach the same yield stress as noted in Portland cement mixtures [43].
2. Sulfoaluminate cement (SAC):
   SAC fulfils a composite superposition effect on the formation of ettringite promoted by gypsum [44]. SAC is a good alternative for ordinary Portland cement (OPC) due to its faster initial setting and final strength development and high early-age strength, which is suitable for 3D printing concrete [45–49]. Wang et al. indicated a 60% reduction in drying shrinkage of 3DCP with an 80% replacement of OPC with SAC [17]. The addition of calcium sulfoaluminate cement was able to control the printability of 3DCP [48]. Aluminate-type cements often have fast setting times [49], which might cause blockage in the printing system during extrusion, even though this property enhances the shape retention. Hence, determination of the setting time is essential before printing to avoid unnecessary blockages within the system.
3. Rice husk ash (RHA):
   RHA can be classified as Class F pozzolan according to ASTM C618 [50] because the combined amount of SiO_2, Al_2O_3, and Fe_2O_3 is more than 70% [38,39,51]. Pozzolanic activity between RHA and cementitious binders occurs when a calcium hydroxide reaches sufficient humidity to generate the calcium silicate hydrate C-S-H that promotes concrete strength growth [39,52–54]. The pozzolan reduces portlandite content to increase the C-S-H gel, improving the resistance [55] and durability of concrete [56–58]. In the process of 3D printing, a high volume of cement and chemical admixtures are generally used, which tends to increase the negative impact on the environment [59]. Rice husk has been chosen by researchers as a potential replacement for cement in 3DCP due to its high water absorption and biogenic carbon [60]. These key features can adjust the fresh-state properties required for the printing process. Their findings indicated delayed hydration with the addition of RHA, which can be mitigated using a suitable alkaline treatment for RHA. RHA mixed cement-based grout indicated enhanced plastic viscosity and yield stress of the mix with the increased proportion of RHA [43]. Researchers found better rheological properties of self-compacting high-performance concrete modified with RHA than the concrete with added silica fume due to its water absorption capacity and porous surface [58,59]. Rheology can be defined as the science of deformation and flow of matter, which expresses the relationship between stress, strain rate, and time [61]. Portland cement replacement by RHA improves the sustainability of a mixture as a construction material. In this work, 20% of the weight of cement is replaced with RHA [62]. Incorporation of RHA has shown a significant improvement in the rheology of mortar at the rate required for construction using 3D printing at a large scale. However, the successful mix designs that contain RHA had shown limitations in replacement proportions [63] and particle size of RHA, as shown in Table 1.
4. Sugarcane bagasse ash (SCBA):
   Agricultural waste can be applied for 3DCP as a green and sustainable approach due to adequate pozzolanic activity and filler effect. In countries where the sugarcane industry produces abundant sources of bagasse waste, SCBA has the potential to be used as cement replacement in 3DCP. Higher water content is required in SCBA-based 3DCP mortar to attain the desirable fluidity and slump [54]. SCBA indicated excellent fresh properties when mixed with cement mortar [53]. However, the strength

properties were reduced when the replacement exceeded 30% of OPC [53]. When evaluating these properties, sugarcane bagasse ash (SCBA) will be another potential successful replacement, which needs further investigation [54].

5. Fly ash (FA):
FA consists of fine particles that are driven out as waste from coal-fired boilers. FA has been used for concrete in construction projects in Australia since the 1960′s [64]. The Australian standard (AS3582.1) [65] stated two grades of FA, Normal Grade and Special Grade, according to the tests described in various parts of AS3583 standards [66]. FA contributes to design and construction by adding values [57,67,68]; workability enhancement, placement, pumping and finishing efficiency, reduced concrete water demand and drying shrinkage, increased long-term compressive strength development, durability and sulfate, chloride and resistance to alkali-silica reaction. FA possesses similar particle sizes (10 to 100 µm) and fineness (300–500 m^2/kg) as OPC [69]. The addition of FA had shown positive effects on the properties of fresh mixture: reduced shrinkage, lower porosity, better mechanical properties and sound durability of printed elements and structures [70]. However, researchers must give their attention to the content of fly ash and their physical/chemical properties in the development phase of mix designs for 3DCP [71]. Effective use of FA as a binder in the range of 45–80% indicated the required properties for 3DCP [72]. A high fly ash content of 70% by volume replacement of cement had shown a negative effect on the mechanical properties of cast products and a positive effect on the extruded products [72].

6. Silica fume:
When silica fume and ground granulated blast furnace slag are added to fly ash-based 3DCP, the rheological properties are improved, resulting in improved structural build-up [73]. Microsilica improves the buildability of the 3DCP by improving the hardness due to enhanced yield stress and viscosity, resulting in improved printability by controlling the shape retention of printed layers [74]. Reiter et al. [75] observed increased packing density of binder when used in 3DCP and a subsequent increase in the yield stress and viscosity of 3DCP with the addition of silica fume due to its higher fineness.

Table 1. Successful mixed proportions for RHA mixed 3D concrete printing.

Reference	[63]	[62]	[58]
Particle size—sand	<1.18 mm	Silica sand <1.7	Not available
Particle size—RHA	<75 µm	2–7 µm	0.075–1 mm
RHA (amount of cement)	20%	20%	15% (Raw Rice husk)
Binder: sand	1:1	1:1.11	Not available
Water: binder	0.48 control 0.45 RHA	0.2 control 0.3 RHA	0.45 RHA
Superplasticizer (% binder weight)	1—RHA mix	0.8—control 0.9—RHA mix	Not available
Viscosity-modifying agent (% binder weight)	Not available	0.15 0.15	0.6%
Flowability Cement/RHA/Sand Cement/Sand	18.35 mm 21.25 mm	12 mm 13 mm	Not available

2.2. Admixtures for 3DCP

Plasticizers, retarders, and accelerators are common in almost all successful concrete mixtures developed for 3D printing (Figure 5). The most used chemical admixtures to increase extrudability and printing quality are high-range water-reducers (HRWR), viscosity-modifying agents (VMAs) and early-age strength enhancers (SE) [76–80].

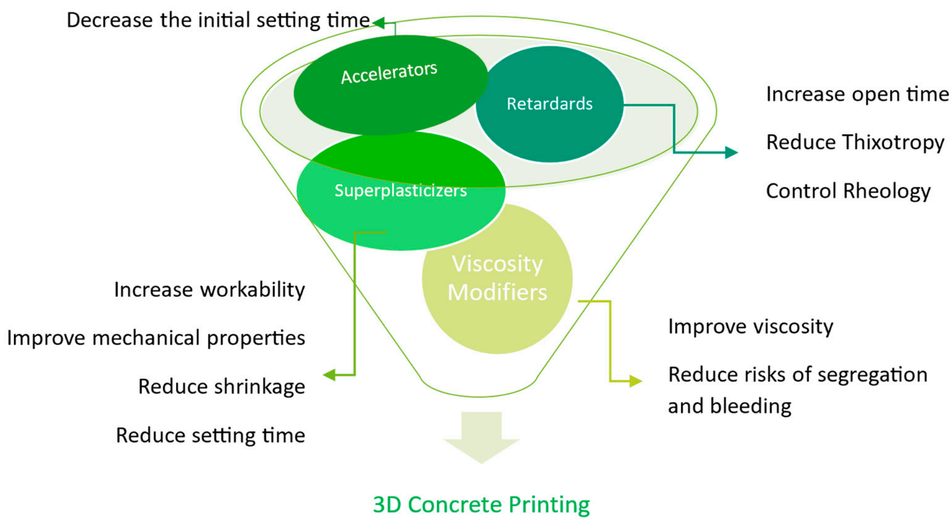


Figure 5. Functions of common admixtures used for 3D printing.

2.2.1. Plasticizers and Superplasticizers

A new chemical admixture called plasticizers was introduced to the construction industry to improve concrete properties [78,80–82]. The initial objective was to reduce the water content in concrete that leads to decreased porosity, which results in reduced shrinkage, enhanced durability, and workability. Lignosulfonate compounds-based plasticizers came to the market as the first generation, which lowered the water-to-binder ratio to between 5% and 10% [83,84]. However, modern plasticizers can reduce the water content in concrete by up to 15%, while superplasticizers allow a reduction in water content by 30% or more. The most popular superplasticizers that have been used in the construction industry can be classified into four major types based on their chemical structure, as shown in Figure 6.

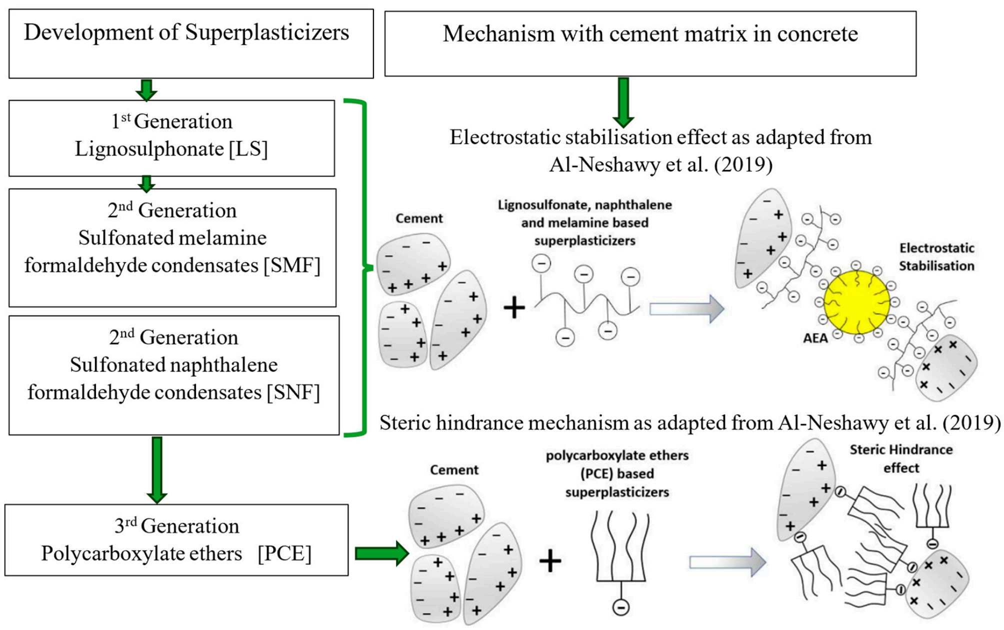


Figure 6. The development of superplasticizers and mechanisms with hydrated cement matrix [84].

Lignosulfonates (LS) are inexpensive, abundant raw materials that contain environmentally friendly polyphenolic crosslinked polymers [85,86]. The addition of LS-type superplasticizers lowered the viscosity of the fresh concrete, facilitating the air escape in the concrete matrix [84,87]. Researchers have shown evidence of reduced ettringite formation [88,89], increased surface area of cement grains [88], delayed hydration process [90] and setting time [91] with the addition of superplasticizers, especially with the poly (carboxylate ether) based PCE type. When the cement particles react with water, the cement grains start to hydrate, accumulating positive and negative charges on the surface of cement particles [81].

According to the macroscopic properties of the dispersion of liquids and solids, the fresh properties, such as viscosity and flowability, are closely related to the properties at the interface between liquids and solids [92]. Plasticizers or superplasticizers cause alterations in interface properties between solid and liquid [93]. The mechanism that takes place within the concrete matrix may be either an electrostatic repulsion effect [94,95] or Steric hindrance [84,87], depending on the chemical composition of the superplasticizer (Figure 6). Hence, the selection of a suitable superplasticizer by carefully looking at the chemical composition and reaction between hydrated cement grains and chemicals in the superplasticizer is a key parameter of ensuring the required properties for 3DCP.

There are varieties of commercially available plasticizers and superplasticizers in the current market. However, fresh properties of concrete mainly depend on the chemical composition, dosage, mixing procedure of superplasticizer and properties of binders (cement + additives). Hence, developing concrete for 3D printing is challenging since the performances are very sensitive to the fresh properties of concrete while ensuring satisfactory strength and service performance. The addition of both superplasticizer and hydroxypropyl methylcellulose provided sufficient buildability, workability, and open time in 3D printing [96,97]. This implies the ability of superplasticizer dosage to control open time for better extrudability and shear strength required in shape retention. Researchers have examined the relationship between open time and shear strength with a dosage of superplasticizers [98].

Melichar et al. [99] used a PCE superplasticizer together with defoaming admixture to decrease the water/cement ratio and increase the physical–mechanical properties of 3D printed cementitious materials. Polycarboxylate-based superplasticizer improved the flowability of the fresh concrete while achieving a water reduction rate greater than 30% [100]. Roussel et al. [101] illustrated that the interactions between the particles in a concrete matrix significantly affect the rheological properties of fresh concrete. During the cement hydration process, phase changes take place, resulting in an anhydrous phase at an early stage, ettringite formation, calcium silicate hydrate (C-S-H) and gypsum, which leads to increased yield stress, thixotropy and hardening while reducing the workability, [89,90,102]. After extrusion, the freshly deposited concrete in 3D printing must recover its original viscosity and yield stress to facilitate the second layer to be placed on it. This clearly indicates the importance of achieving buildability while maintaining extrudability. Since these properties are very sensitive to the chemical reaction between cement grains and chemicals in superplasticizers, it is essential to ensure a proper mix design without only depending on the technical specifications of materials. No research focusing on the chemical reaction of concrete mixtures, especially designed for 3D printing incorporating waste-based additives and superplasticizers, can be found in the literature.

Other key concerns are the selection of correct dosage and mixing procedure to avoid high fluidity, which causes bleeding and phase separation of concrete. Ma et al. [92] suggested using viscosity-enhancing compounds with superplasticizers to eliminate such drawbacks. Superplasticizers can change the shear thinning of the concrete to shear thickening, which is a key need in concrete printing [13]. Since a range of types of cement with various chemical compositions are available in the market, it is essential to verify the performance with the manufacturer's specified superplasticizer dosage. This is because the chemical reaction in hydrated cement paste with the added superplasticizer may cause adverse effects, especially in maintaining good extrudability and shape retention.

2.2.2. The Viscosity-Modifying Agent (VMA)

The most common viscosity-modifying agent (VMA) used in digital printing technique is derived from cellulose ether. VMA enhances the compressive strength of the cementitious matrix at a fresh state and controls the deformation of printed layers during printing [103,104]. These admixtures are exploited as nucleating agents, absorbing cement particles and linking them to develop large flocculants, resulting in a restricted flow of fluid layers and increased plastic viscosity and yield stress [105]. Clay is an effective rheological modifier in 3D printing because it enhances the stiffening rate of cement composites at rest, even though it reduces the apparent viscosity under shear [106]. Hydroxy-propyl-methylcellulose (HPMC) enhanced the yield stress and viscosity of the mixture, which further increased the shape retention [44,107].

2.2.3. Retarders and Accelerators

The retarder decelerates the hydration process to minimize the variations in the rheological properties of fresh concrete. This additive can facilitate the transportation process by delaying hydration. The retarders that have commonly been used for concrete are organic retardants. Several examples include refined calcium, sodium, NH4, salts of lignosulfonic acids, hydrocarboxylic acids, and carbohydrates. The additives that affect the material buildability are the accelerator and the viscosity modifier; the former helps the extruded concrete to obtain a short setting time to bear the stress from the upper layer [108], and the latter enhances the viscosity and cohesion of the material to improve the stability of the extruded shape [108]. Increasing the dosage of these additives will result in delayed solidification of deposited filament, which helps shape retention in printing.

2.3. Fibers for 3D Printing

Fibers can be introduced to 3DCP to achieve high mechanical strength and shape stability by controlling the rheological parameters [109]. The fibers in the cement matrix control shrinkage and cracking, resulting in improved toughness of concrete [110–112]. The mixture's microstructural morphology and constituent characteristics are the root of all mechanical properties. The superior properties in Fiber-reinforced concrete (FRC), such as high strength to delay the first crack, improved tensile and ductility, and resistance to shrinkage cracking, will contribute to eliminating drawbacks in 3DCP, especially as an alternative solution to the provision of steel bars. Various fibers, especially polymer fibers, have been used for investigations on 3DCP. Polymer flexibility may facilitate better extrusion without blockage when compared with the metal fibers for 3DCP applications. The most common polymer fibers that have been used are illustrated in Figure 7.

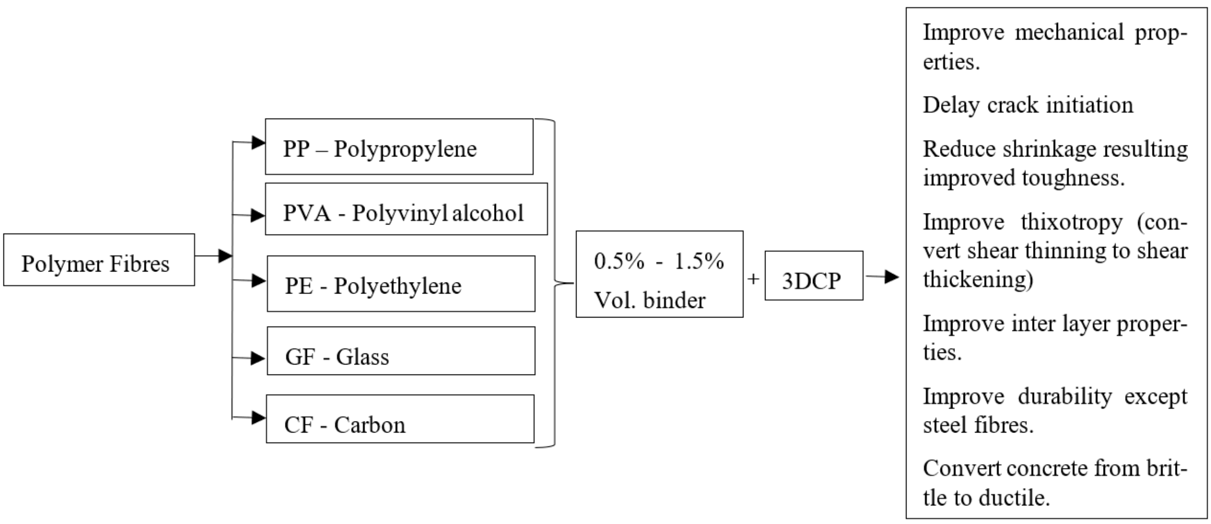


Figure 7. Illustration of fibers addition and improvements in 3DCP.

PP and PVA fibers (fiber content 0.5% to 1.25%) increase the yield stress and improve the thixotropy of calcium sulfoaluminate cement composites [110–112]. The 3D printed concrete with fibers indicated excellent properties compared to concrete without fibers [109–113]. Added fibers influence both fresh and hardened properties of concrete. These fibers improve shrinkage resistance, which is required to reduce stresses at inter layers in printing, microstructure, and mechanical properties of concrete, even though a slight reduction appears in workability. The key influencing parameters are fiber type, geometry, fiber size and volume in concrete [81,82]. Kim et al. [114] investigated the behavior of polyethylene terephthalate (PET) fiber reinforced concrete and found a considerable reduction in shrinkage cracks. Polypropylene fibers (PP), with length and diameter ranges from 5 to 30 mm and 5 to 100 μm, respectively, can effectively control shrinkage in concrete [115]. Extensive research studies have been recorded on exploring the suitability of different fibers in cement matrix to improve fresh and hardened properties of concrete. Hombach et al. [116] studied the performance of 3D printed fiber reinforced concrete. Their study was based on carbon, glass and basalt fibers and the fiber length ranged from 3 mm to 6 mm and showed enhanced flexural and compressive strength up to 80 MPa without affecting the printability of concrete. The ability of the extrusion nozzles to align fibers into the print path has caused a considerable increase in the flexural and tensile strength of 3DCP structures [117]. Carbon fiber reinforced concrete reported a remarkable strength gain. No blockage of the printing nozzle was noted during the printing process till the fiber volume was less than 1.5% of the cement volume. Carbon fibers (1% Vol. of binder) reinforced concrete had shown a maximum yield stress of 30 MPa at 0.42% deformation, while the plain cement reaches 10 MPa yield stress at 0.058% deformation. This clearly indicates the importance of introducing fibers into 3D printing process.

Sing et al. [118] used 200 μm diameter 13 mm long steel fibers up to 1% vol. and revealed reduced slump and improved buildability with the addition of nano clay, which acts as an interlocked web due to an increase in the friction and adhesion among particles. On average, 1% of PE fibers (12 mm long, 25 μm diameter) showed the highest spread diameter, and the samples with 1.5% PE fibers showed optimum mechanical properties [119]. Li et al. [120] used glass fibers (14–19 μm Dia. and a length of 12 mm) and basalt fibers (13 μm and a length of 12 mm) for 3DCP, which contains coral sand. The mix design with 1% of fibers showed optimum buildability and flexural and compressive strengths. Adding 1% polyethylene (PE) fibers can change the failure mode of 3DCP from brittle to ductile with better deformation [121]. PVA in 3DCP showed reduced fluidity due to interlocking and entangling behavior among fibers in concrete mixtures [110,122]. Investigation on the 3D printed lightweight engineered cementitious composites, incorporating 1.75% PVA, indicated reduced workability and increased setting time [123]. Shakor et al. [13] showed an 11.52 MPa increment in compressive strength by adding 1 to 1.5% glass fibers. However, Hambach et al. [116] provided contradictive results, which showed increased flexural strength by 1.8 MPa and decreased compressive strength by 20 MPa by adding 1% glass fibers [116]. Researchers have used PVA fibers up to 18 mm in length, and performance was noted up to 1.5 vol.% of PVA fiber addition [109,123,124]. 3DCP containing PP fibers effectively increased the yield stress (dynamic) and plastic viscosity of concrete mix [85,86]. In these studies, 12 mm long fibers with diameter ranges from 7 μm to 19 μm were used in addition to PVA fibers into 3DCP to enhance the ductility and crack resistance while achieving high strength [100].

It Is predicted that using fibers, especially hybrid fibers, not only covers the deficiencies of initial cracking of 3DCP but also can be used instead of steel bars; therefore, this material can play a pivotal role in the construction industry's future. When PVA fibers were added to the cement matrix (up to 1.5%), the compressive strength increased to be almost double with the addition of activated carbon powder (up to 1.5% wt.) [110]. Adding fibers into concrete can significantly improve the crack resistance of concrete, ensuring the continuity of 3D printing. However, the direction of fiber distribution in the concrete matrix can affect the efficiency of stress transfer in the matrix. Studies showed that adding steel fibers with proper length can effectively improve the flexural properties of 3DCP compared to that of short glass fiber usage [105,125]. The type of polymer used depends on the intended application and requirement for concrete properties [126]. Fibers contribute to improving flowability [127], setting times [128], mechanical properties [129,130] and concrete microstructure, in addition to controlling shrinkage [131,132].

These research studies clearly showed that the addition of fibers into 3DCP improved performance in pumpability, flowability, and consistency in extrusion-based printing. In the early studies, the researchers initially faced challenges in the decision-making process of selecting fiber size, optimum proportion, and correct print head speed to avoid any blockages with the available nozzle size while achieving the required fresh and hardened properties and maintaining consistency for their intended mix design. Table 2 summarizes existing studies that successfully printed concrete with the addition of fibers such as steel [118,133], PE [5,121,134], PP [13,109,135], PVA [100,110], glass and carbon [136]. This may help researchers lay a strong foundation for proposing and selecting suitable fibers for 3DCP.

Table 2. Selected fiber properties and printing properties.

Fiber Type	Length (mm)	Diameter (µm)	% Vol. of Cement	Nozzle Size (mm)	Printing Speed (mm/s)	Reference
ST	13	200	1	20	20	[118]
ST	6	200	1	-	130	[133]
PE	6	20	3.5	30	50	[134]
PE	12	20	1	30	22.5	[121]
PE	12	27	0.33	-	-	[5]
PP	6	50	0.75	2.7	10	[109]
PP	6	30	1	25	60	[135]
PP	6	100	1	14	-	[13]
PVA	9	31	1.2	-	30	[100]
PVA	12	39	1.5	-	-	[110]
Glass	12	7	0.5	40 × 25	-	[136]
Carbon	6	7	0.5	40 × 25	-	[136]

2.4. Fluidity Requirement

The minimum stress required to initiate and maintain the flow can be defined as static and dynamic yield stress, respectively. The resistance provided by a fluid to flow freely is known as the plastic viscosity (µ), which implies the additional shear stress required to increase the flow rate [16]. When the external shear force is removed, the concrete stops flowing, and the flocculation of the particle will commence due to the interparticle interaction, and the static yield stress is restored. This is known as the thixotropic behavior of concrete [137]. The structural build-up is the evolution of yield stress with respect to time [137]. The increase in viscosity with the increased shear rate is known as the shear-thickening behavior, and vice versa is the shear-thinning behavior [138]. 3DCP requires shear-thickening behavior, although traditional concrete has shear-thinning behavior.

The chemical reaction in the concrete matrix would not be completed, resulting in weaker strength if the water content is low. However, excessive water should be avoided because it reduces the strength and buildability of 3DCP [63]. The longer final setting time of 3DCP contributes to the smooth flowability, extrudability, and reduced buildability and strength between layers resulting in structural collapse. Hence, it is essential to identify the correct fluidity level, which is required for successful printing. The Chinese standard recommends fluidity between 160 mm and 220 mm for printing mixtures having aggregate sizes less than 5 mm [139]. Figure 8 as illustrated in [100] shows the appearance of 3DCP mixture with fluidity level, which helps researchers physically determine the correct mixture with observations.

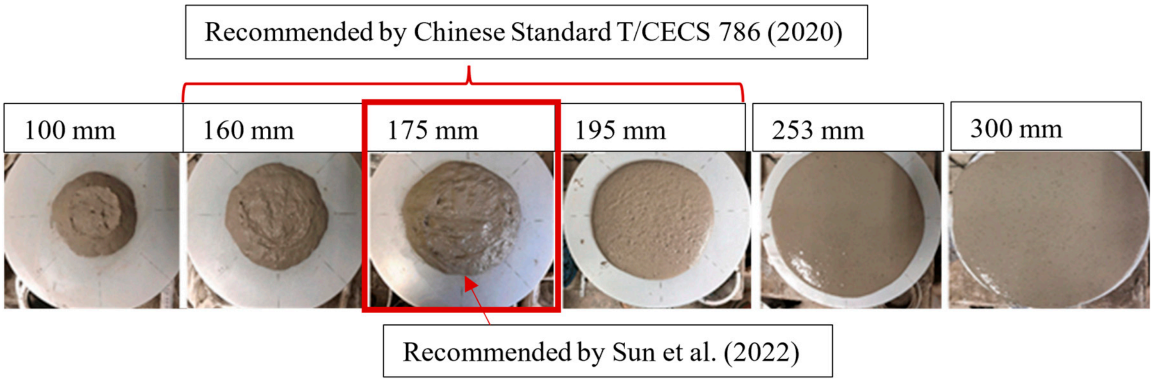


Figure 8. Fluidity Vs appearance of the mixture and recommended fluidity of 175 mm for 3DCP [100,139].

Fine powder additive mixtures can densify the concrete structure by filling voids and pores, hence improving the flowability of concrete [63]. However, the partial replacement of cement by RHA reduces the flowability of the mix due to its porous nature, which absorbs physical water from its surroundings, resulting in the densification of the cement matrix [63].

2.5. Aggregate Size and Aggregate to Binder Ratio

Printable concrete is a high-yield stress material that is sensitive to the aggregate: binder ratio content in the materials. Mohan et al. [140] showed a significant increase in plastic viscosity, yield stress and storage modulus with an increased aggregate-to-binder ratio. However, the material should be sufficiently flowable for continuous pumping without any phase separations or blockages. Printing concrete with coarse aggregate caused cracking of printed materials and resulted in brittle interfaces between layers [141]. On average, 30% by volume of coarse aggregate size with a maximum size of 10 mm in 3DCP mixture showed good extrudability without any blockage or filament failure [142]. Researchers [143] reported printing of 10 layers without any obstruction in the 3DCP with coarse aggregates of a maximum size of 8 mm. Lightweight aggregates (LWAs) are made of a variety of sources: perlite, vermiculite, expanded clay, fly ash pellets, coconut shells, oil plum shells, rubber, ceramic wastes, etc. [144]. Senff et al. [145] investigated the effects of LWAs, perlite and vermiculite on the rheological properties of 3DCP. The measured yield stress was proportional to the aggregate ratio. However, the majority of research studies with successful mix designs were performed using aggregate sizes less than 2 mm. Several selected mixed proportions are shown in Table 3.

Table 3. Selected successful mixed proportions and mechanical properties.

Ref.	Fiber	% vol.	Silica Fume (g)	Cement (g)	Aggregate (g)	Water to Binder	Super-Plasticizer	Other	Flexural Strength (MPa)	Compressive Strength (MPa)
[118]	ST	1	-	1000	1000	0.35	1.32 g	Nano clay 1.8 g + retarder	-	40/36
[133]	ST	1	268	483	1074	0.24	10.7 g	Ground Granulated Slag 322 g Retarder 6.44 g	15	109
[134]	PE	1	-	1000	1000	0.35	1.28 g	Accelerator and retarder	14	-
[121]	PE	1	-	1000	1000	0.35	1.28 g	-	-	27.3
[109]	PP	0.75		-	-	-	-	-	9.5	58
[135]	PP	1	81.4	562	1144	0.32	4 g	Fly ash 162 g VMA 2g	-	60.5
[13]	PP	1		375	375	0.33	2.5 mL	Retarder 2 mL/accelerator 2.5 mL	18	68
[100]	PVA	1.2	100	1000	-	-	-	-	14	74.16
[110]	PVA	1.5	110	1000	1330	0.27	11	Fly ash 1330	10.81	45.05
[136]	Glass	0.5	101	806	1027	0.29	-	Metakaolin 101g		115

3. Challenges, Opportunities, and Current Progress of 3DCP in Australia

3DCP has proven to be the future construction method in achieving sustainability goals and fast-tracking Australia's transition to net zero by 2050. It has the potential to offer automated prefabrication from factories to large-scale construction at site. The advancement of 3DCP in the Australian construction industry is still emerging. This section reviews the literature of the past seven years on the challenges of 3DCP and how they are relevant to the Australian context, as described below:

(a) Impact on traditional construction workers and a need for a digitally skilled workforce

Australian Bureau of Statistics reported that there are 1.32 million construction workers (data as of February 2023), representing 9.6% of overall workers in Australia [146]. With the increase in government-funded infrastructure projects in the next decades, there will be a massive demand for tradies and building materials that will impact residential construction and home builders. The target to achieve 1.2 million new homes will be at stake due to high competition for key trades and skilled workers from the higher-paying infrastructure sector [147]. This is echoed by the Housing Industry Association Ltd. report, which emphasizes the severe shortages of skilled trades in the residential building industry [148].

3DCP offers excellent opportunities to address the challenges of labor shortages in the residential construction sector. Adopting this technology will reduce the amount of labor due to improvements in the construction rate, higher-level automation, and shorter construction time [149–152]. This is an opportunity, especially in remote areas where there are limited tradesmen and the workforces are heavily relying on fly-in, fly-out workers [150,151]. A reduction in labor will also lead to enhanced construction safety with fewer injuries and fatalities, reducing labor cost by 50–80% [153]. However, some skilled workers, such as in concrete mixing, pouring and steel reinforcing, will be facing job displacement [154,155].

The 3DCP construction technology requires new skillsets and talents at the design and operation stages. The existing construction workers require re-training and learning new skills such as modelling, communicating with robots, operating, regulating, and maintaining 3D printers, with an in-depth understanding of printing parameters and concrete thixotropic behavior. These skills cannot be replaced with a lower-skill workforce [156–159]. These are more challenging in Australia's remote communities with lower literacy and numeracy skills [150]. Overall, investment to upskill the Australian workforce is critical to meet the demand for digitally skilled talents through vocational, undergraduate, and postgraduate courses to lead the future digital construction.

(b) Initial capital cost of printers and printing limitations

The high capital cost of 3D printers and infrastructure is one of the main restraints for small and medium construction companies to venture into the technology [150,154]. It is estimated the cost of construction 3D printer can be approximately USD 180K to over USD 1M [160]. With the growing global acceptance by major players in the industry, increasing start-up companies, and large-scale adoption, the equipment cost of 3DCP is expected to be lower than conventional construction [161]. Studies found the allocation of equipment cost of robotically built walls is estimated at 18% of the total cost [162].

In addition, the size of 3D printer and geometric capability may limit the size of the printed structures, which is not favorable for large-scale construction [82,150,158]. The gantry system is mostly used due to the greater flexibility of printable dimensions, compared to limited arm distance in the Robotic Arm method [158] and the slightly cheaper approach for printing complete structures [163]. No limit of printable dimension in driving direction (x), between 10 to 50 m in the y-direction and up to 8 m in height (z-direction), was reported [82]. Some flexibilities are allowed for 3D printed precast concrete elements but are still not capable of printing medium-rise multi-storey buildings [164]. The transportation of 3D printers will escalate the costs further if the projects are far apart, especially in remote areas in Australia [150].

(c) Lack of standards and government support

3DCP is still an emerging technology and there are no specifications and design standards in Australia and globally. The regulations and policies have yet to be fully developed, which has a negative impact on rapid commercialization and hinders its full adoption [152,154,165]. To meet the industry requirement, the current standards need to be applied for fabricated components [155]. As a starting point, a separate chapter in existing standards can be incorporated, such as in AS3600 [166] or AS 3850 [167]. Standards for material testings, structural performance under various loading and exposure conditions, durability in service and specifications for reinforcing systems in 3DCP elements are needed, especially for large-scale applications [4,152,158,165,168]. A few committees are currently developing design standards, including ISO/ASTM 52939 on Additive Manufacturing for Construction Qualification Principles Structural and Infrastructure Elements [169], ACI Committee 564—3D Printing with Cementitious Materials [170] and RILEM Technical Committee 276-DFC on digital fabrication with cement-based materials [171].

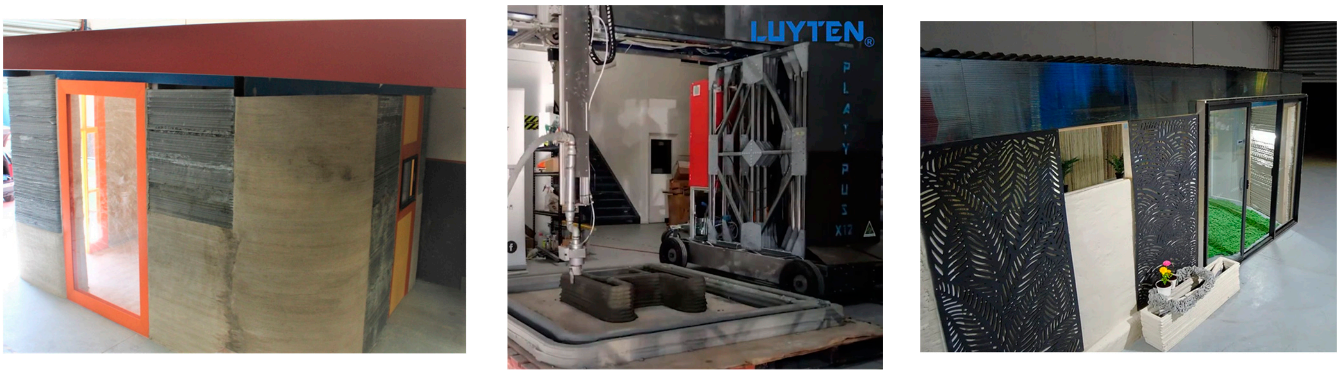
Government support is critical in promoting and realizing the adoption of 3DCP in the construction industry. Worldwide, governments are prioritizing additive manufacturing, including concrete 3D printing, such as the release of a strategy for the technological advancement of additive manufacturing by the United States Department of Defence in 2021, Dubai 3D Printing Strategy 2016 with a target of 25% new buildings constructed using 3DCP technology, China 14th Five-Year Plan with expansion of large-scale 3D printing construction projects and increase government research funding [172]. The government of Singapore established a SGD 80 M Singapore Centre for 3D Printing at Nanyang Technology University (NTU) to support research in the aerospace, marine and offshore, building construction and process management industries [173]. In Australia, CSIRO released the Advanced Manufacturing Road Map in 2016, where 3D printing is one of the cores enabling technologies to achieve the plan for the next 20 years [174]. The latest trend of additive manufacturing in Australia is showing a very positive outlook, with business expanding through federal and state government grants. In construction, the trend of 3D concrete printing is heading in a positive direction. Recently, through the Australian federal government's Cooperative Research Centres Projects Grants program, Luyten has collaborated with the University of New South Wales (UNSW) and Hanson Construction Materials (Hanson) to develop 3D printed houses in remote Australia to support mining and other communities [175]. A search using the keyword "3D printing" in the Australia Research Council (ARC) data portal [176] yielded 113 additive manufacturing research projects in various applications such as aerospace, manufacturing, healthcare and automotive. However, only nine projects are specifically on 3DCP, funded from 2016 to 2024, majority to the Swinburne University of Technology. Clearly, more supports are needed from the government for the 3DCP to thrive in Australia.

(d) Solution for house affordability and shortages

3DCP possesses greater benefits to the Australian construction industry, particularly in addressing house affordability and shortages in the current climate where supply chains, material costs and labor shortages are challenging issues. Significant advantages of 3DCP, such as up to 78% cost savings and a 60% reduction in labor, can be achieved [154]. A reduction in cost due to formwork elimination and associated waste is another bonus point, which can save up to 63% of the project cost [11,149]. Analysis of five construction techniques, i.e., in situ Reinforced Concrete (RC), Hot Rolled Steel (HRS), Cold-Formed Steel (CFS), Prefabricated Concrete Construction (PCC) and 3DCP of building two-storey villa with an area of 219.3 m^2 revealed that 3DCP offers the most economical solutions [163]. Cost reductions of 21%,10%, 15% and 24% can be gained compared to PCC, RC, CFS and HRS, respectively. In 2023, Australia's population expansion is estimated at 500,000 due to a surge in migration. Based on this expansion, at least 190,000 to 200,000 housing need to be completed [177]. 3DCP offers huge time savings in housing construction. For example, Fortex Pty Ltd. estimates the printing time for a 210 m^2 single-storey three-bedroom and two-bathroom house requires only 70 h to print the entire wall system. Delays due to supply chain can be avoided and the material selection can be adjusted to rely on locally available raw materials [178]. Further material cost reduction can be realized through utilization of waste or recycled materials as the primary raw materials [179,180] with improved sustainability through carbon sequestration [157].

(e) Current practice and progress of 3DCP in Australia

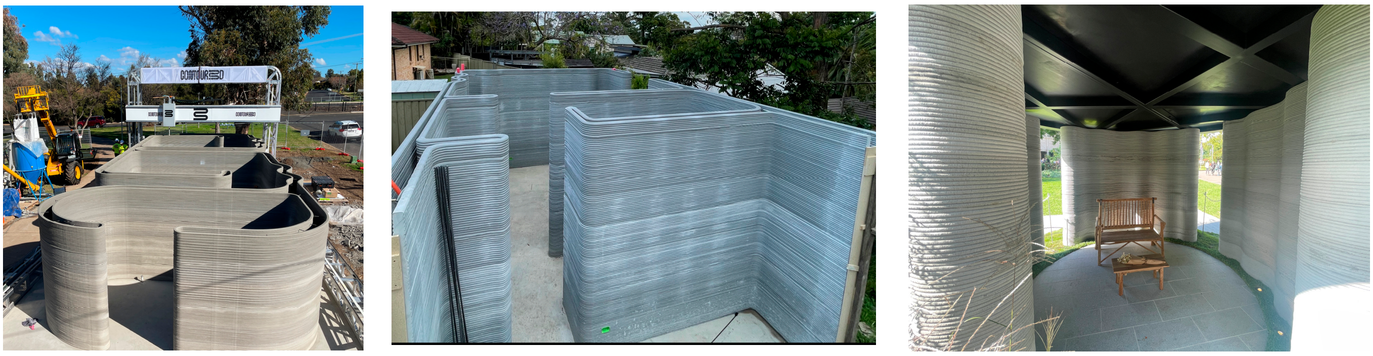
The industry adoption of 3D concrete printing in Australia has been gaining in the past 4 years. However, only limited companies are leading 3D concrete printing for construction of small-scale structures such as single-storey houses, eco-cabin, granny flats and pods. In August 2022, Luyten built the first 3D-printed indigenous housing project (Figure 9a), located in an extreme climate in the Northern Territory [181]. Using a proprietary concrete material called Ultimatecrete, the material is capable of withstanding extreme weather conditions. The construction was materialized using a large mobile 3D smart AI-powered concrete printer (12 m wide × 6 m high) called Platypus X12 (Figure 9b), which is capable of printing two-bedroom houses in just 22 h. The company aims to build 30% of housing in Australia's regional areas using 3D printing technology by 2030. Luyten also printed a 3D single-storey house called 'Heptapod' (Figure 9c), which can be printed in two days. The printed elements gain sufficient strength after 5 h at a fraction of the cost. Huge saving of production time, and 80% of labor costs can be achieved.



(**a**) 3D printed Indigenous house project (**b**) Platypus X12 mobile printer (**c**) Heptapod house

Figure 9. 3D printed structures and printer used by Luyten [181]. Reprinted with permission from [181]. 2024, Luyten.

Contour3D is another leading company in Australia in the 3DCP industry. The construction method is based on contour crafting using dynamic mobile gantry printer called Opus One. The printer has a building envelope of 24 m long × 13 m wide × 6 m high. A proprietary concrete material called ContourCrete is used for printing the walls, which contains 40% recycled materials. The materials are claimed to have inherent strength that can double the usual life expectancy of a standard home. Several projects have been completed, including amenities blocks, granny flats, and pods (Figure 10). The Opus One printer is capable of printing walls in a few days, and 3–4 bedroom homes are ready to be occupied in 8–10 weeks. Printing of a 50 m^2 granny flat only used 18 tons of Contourcrete with 15 h of actual print time. The printing of two pods and BBQ bench in the factory took 10 h and was transported from Sydney factory to the Melbourne Garden Show [182].



(**a**) Amenities block (**b**) Granny flat (**c**) 'Lunaria Pods'

Figure 10. 3D printed projects by Contour3D [182]. Reprinted with permission from [182]. 2024, Contour3D.

Another enterprise that has recently entered the field is Fortex Pty Ltd. Fortex is the exclusive Australian distributor of COBOD 3D construction printers. Fortex aims to introduce COBOD International's 3DCP technology into the Australia residential market to meet the housing demand and combat the issues of supply chain and shortage of materials. Improving productivity through the reduction in the construction period and optimizing the material are several key targets. Fortex estimates to print the entire wall system of 210 m^2 single-storey three-bedroom house in just 70 h [183].

Macro3D is also one of the pioneers, providing 3D concrete printing in Australia. Macro3D offers integrated solutions for 3D concrete delivery systems using a mobile robotic arm, high-resolution mortar mix and cloud-based printing software with a parametric design function [184]. The first 3D printed build was a 60 m^2 Class 10 structure with a further 60 m^2 undercover area (Figure 11a), printed using a mobile printer (Figure 11b).

(**a**) 3D printed structure (**b**) Mobile printer

Figure 11. Macro3D project and mobile printer. Reprinted with permission from [184]. 2024, Macro3D.

Overall, due to the challenges described above, wider adoption of 3DCP in Australia has not yet materialized. Comprehensive studies on cost–benefit analysis in the Australian context are required to convince the industry players to implement 3DCP as a viable and economical construction method in the future. In addition, procurement rules to endorse sustainable 3DCP construction techniques, collaboration with policy makers, dissemination of knowledge on societal benefits of waste incorporation, and linking environmental, economic and social benefits of expanding this sustainable technology will strengthen the development efforts of 3DCP as highlighted in sustainable concrete construction approaches by Mehran and Ciaran [185].

4. Discussion

Many research studies have been focusing on developing fresh properties of the 3DCP mixture. Review articles that help to understand the status of knowledge in 3D printing have also been specialized under specific themes: usage of supplementary materials [51,69,186], introducing fibers [81,82] and admixtures [187] and providing an overview of developed mix designs [130]. The fastest way of developing a technique is learning from failure. Hence, it is important to identify the critical problems and drawbacks in the system, as well as causes and attempts to overcome such issues. The status of current knowledge of constituent materials to develop 3D printing concrete technology into green and sustainable direction, their effects on fresh and hardened properties of 3DCP, the drawbacks in the system and attempts to overcome such problems are analyzed. Installing reinforcements in 3DCP is generally not a feasible task [98,187]. The development of a good mix design with required tensile and flexural properties may successfully overcome this issue [188,189].

Exposure to plastic shrinkage in the early stage after printing is another key issue [190,191]. High binder content in the mixture resulted in high shrinkage. The most common pumping system that has been used for 3D printing is the screw pump which does not allow the use of coarse aggregates. Hence, the printable mixtures contain a high binder content (more than 800 kg/m^3), while the conventional concrete with a similar grade contains a low binder content of 400 kg/m^3 [140]. The addition of cementitious supplements to limit OPC or replacement of OPC using SAC will be a sustainable approach. Simultaneously, the development of a mechanical pumping system to suit major constructions is also a timely need together with a focus on the design of concrete mixture.

The fresh properties of 3DCP can be categorized as fluidity, cohesiveness, and water retention [192,193]. Ensuring continuous and even extrudability while achieving required thixotropy and setting times is another challenging task. A weaker interface due to voids resulting from mechanical anisotropy can be controlled by introducing fibers into a concrete matrix [119]. Concrete should reach sufficient yield stress after extrusion for shape retention. Incorporating properly selected fibers into 3DCP can reduce spalling, restrict deformations, and improve uniform and continuous printability [97,194–196].

Liquid-phase segregation during the extrusion of the nozzle [196–200] badly affects the rheological behavior of concrete. This is mainly due to the pressure loss in pumping resulting from the formation of a lubrication layer during the pumping phase. A low shear zone was created in the central pipe area, while a high shear zone formed at the proximity of the pipe perimeter. Aggregate particles in the concrete move from the high shear zone to the low shear zone due to shear-induced particle migration [201]. This results in the formation of a binder-rich lubrication layer of a few millimeters near the pipe wall [202]. This indicates the importance of considering the effect of the lubrication layer when predicting the pressure loss in concrete pumping. In the mix design process, selecting printing parameters is equally important for successful 3D printing.

Printing process parameters such as printing layer interval time, moisture level, speed and height of printing head, geometry and rotational velocity of the spiral blades, extrusion shape and size are sensitive parameters that control the quality of printed objects [13,82]. Among them, a mutual influence can be seen between the interval time of the printing layer, surface moisture content and the travelling speed of the print head. Stating process parameters in mixed design approach-based research articles is important to lay a sound base for future research studies.

Qingxuan et al. [203] investigated the effect of travel speed and height of print-head on the mechanical properties of 3DCP and found a decrement in compressive and splitting tensile strength with the increase in travel speed and height. Similarly, Panda et al. [204] illustrated the reduced tensile bond strength of 3DCP with increased travelling speed and height of the print head. Yu et al. [205] studied the characteristics of printed interfaces based on the pore structure of 3DCP using the mercury-pressure method and X-ray CT scans. The results demonstrated that the slow movement of the print head, the absence of vibrations, and rapid moisture loss can cause higher macroscopic porosity and larger-sized pores in 3DCP as well as more irregular and elongated pore morphology [205]. They noted an increase in the total porosity from 22.8% to 32.6% for mold-cast concrete and 3DCP, respectively. Brittle failure of printed material should also be avoided. Adding polymer fibers would change the failure mode from brittle to ductile.

The high porosity of printed material indicates lower strength than the mold-cast samples from the same batch. The printed concrete is subjected to no vibration, little compaction after pumping and filament deposition in the extrusion process, which results in increased air entrapment. A study found the measured total porosity of printed and cast samples was 10.8% and 6.5%, respectively [135]. The majority of these pores were in the interlayer regions. Water migration due to surface moisture evaporation between printed filaments, surface roughness, and the thixotropic pattern of 3DCP also cause increased porosity and void interconnectivity. The nozzle parameters also caused such problems.

Weaker interfaces between filaments and filaments tearing are common problems in 3D printing. Particle migration and segregation of water from the fines paste due to the hydraulic pressure gradient and formation of a lubrication layer during the extrusion of stiff materials are reasons for creating voids, pressed, and smeared between filaments resulting in weaker interfaces and filament tearing due to incompatible printing parameters such as high print speed coupled with a lower extrusion rate [135].

Another reason for weaker interfaces is the sensitivity to the fluidity of the mixture, which reduces the extrudability of the material and bonding strength between the layers and strips. Liu et al. [206] found decreased tensile strength and inter-laminar bond strength with increased interval time between layers before the final setting. They also noted increased shear strength and negligible changes in tensile strength after the final setting. Severe moisture loss on the surface reduces the interfacial humidity, causing a reduced rate of hydration resulting in increased porosity of the sample [206]. Le et al. [207] examined the anisotropy of 3D printed concrete using compressive and flexural strengths and the interfacial bond between layers. They noted decreased compressive and flexural strength of 3D printed material in the vertical direction of printing. The increased interval between printed layers had caused decreased interlaminar tensile strength between printed layers even though an increased flexural strength along the printing direction was observed.

Acceptance of 3DCP into the construction mainstream has been widely gaining in recent years. However, this technology has been centralized only in several parts of the world with limited large-scale applications. As with almost all new technologies, the high capital investment cost at this initial stage has attracted less attention from many nations. The lack of guidelines and limited capacities of construction equipment related to this technology has hindered broad applications in civil infrastructures. Hence, it is extremely important to consider simultaneous approaches to the development of printing equipment and robots with enhanced capacity for an affordable cost. Collaboration between academia, industry, professional bodies, standards associations and policy makers is deemed important in developing economical and sustainable 3DCP materials and techniques for broad acceptance.

5. Conclusions

3DCP is a green and sustainable technology that was introduced to the construction industry over nearly a decade. This paper critically reviewed existing literature on the development of sustainable concrete mixtures. The material and construction-related drawbacks are identified and suggestions to improve this technology are presented by critically comparing the published research articles on developing 3DCP technology. The progress and applications of 3DCP in the construction industry, especially in the Australian context, are also reviewed. The following key aspects of developing this technology for acceptance by the broad construction spectrum have been identified:

1. The performance of printed objects depends not only on the correct mix design but also on climatic conditions such as humidity and temperature in the construction phase and printer parameters such as size, geometry, operating mechanism, printer head details, nozzle size, shape, speed, and filament parameters (number, width and

height of layers). Stating all these factors on material and structural performance in research publications is essential in maintaining consistency in the development chain to accelerate the progression of this technology as a global team effort.

2. The use of high OPC content and the development of mixtures without a broad understanding of both mixture and printer performance hinders the expansion of 3DCP in large-scale construction applications. Using LC3 and SAC as alternatives to OPC can reduce the environmental effects and increase the required fresh properties of the 3DCP mixture, resulting in improved printability.
3. Use of Pozzolanic waste materials such as FA, RHA and GGBS with controlled particle size and dosage to partially replace OPC will improve the packing density of the mixture and subsequently will increase strength and durability. However, weaker properties caused by adding waste can be controlled using additives, superplasticizers and well-graded waste materials.
4. Almost all successful 3DCP mixtures contain chemical admixtures. VMA improves the viscosity while reducing the segregation/bleeding during extrusion. Superplasticizers address the majority of common problems in fresh and hardened properties of mixture. Depending on printer parameters, scale of printing object and corresponding batch, retarders and accelerators can be used to alternate the open time of printer while controlling the rheology.
5. Plasticizers are capable of reducing the water content in concrete mixtures up to 15% while the superplasticizers can control about 30% or more. However, it is extremely important to identify the chemical composition of the binder and the reaction of the superplasticizer in the cement matrix before selecting a suitable plasticizer or superplasticizer. Even though the technical specification of the product provides dosage and mixing requirements, conducting pre-trials to determine the suitability of the recommended dosage for the selected cement brand is a learned decision.
6. Selecting fibers in the range of 0.5%–1.5% of binder volume with suitable size (length and diameter) to suit the nozzle parameters can effectively eliminate many drawbacks in 3DCP. Literature reveals that adding polymer fibers at least 6 mm length can improve the fresh and hardened properties of the 3DCP mixture. Using hybrid fibers in the 3DCP can effectively eliminate the reinforcement requirement of structural applications. However, further investigations are needed.
7. The fluidity of the mixture plays a major role in controlling the printability and buildability of 3DCP. The Chinese Standard recommends maintaining fluidity between 160 mm and 220 mm for better extrudability and printability. Researchers had identified 175 mm of fluidity as an optimum level.
8. Printable concrete is susceptible to the aggregate content in the mixture. The use of coarse aggregate has caused cracking and brittle failure of interfaces of the printed object. Literature suggests limiting the maximum aggregate size to 10 mm. However, most successful mix designs controlled their aggregate size to 2 mm or less. This might be due to the restrictions in printer parameters.
9. The accelerated way of developing a new technology is learning from failure. Hence, it is important to provide main concerns on drawbacks, reasons, and the ways of overcoming them by modifying or inventing, which is a timely need in expanding 3DCP for major constructions in an accelerated manner. A simultaneous approach to the development of the printing head and the machine parameters with the mixture is essential for sustainable applications of this technology without borders.
10. In the Australian context, 3DCP is a promising solution for residential and building constructions to achieve net zero by 2050. Key challenges, including digitally skilled workforce, high capital cost, design standards and government support, need to be addressed for wider adoption of this technology in the construction industry.
11. Collaboration between industry and academic researchers and government support are imperative to facilitate successful 3DCP materials and technology. Otherwise, research-based developments in the laboratory environment may not be feasible for

economical and large-scale construction applications. In addition, the appointment of technical committees in different parts of the world may help to expedite the development of design guidelines and specifications for rapid commercialization and broader adoption of 3DCP.

Author Contributions: Conceptualization, K.G. and N.H.R.S.; methodology, K.G. and N.H.R.S.; investigation, K.G., S.F., T.Z., M.B.F.T. and N.H.R.S.; data curation, K.G.; writing—original draft preparation, K.G.; writing—review and editing, K.G., S.F., T.Z., M.B.F.T. and N.H.R.S.; visualization, K.G.; supervision, N.H.R.S.; project administration, N.H.R.S.; funding acquisition, N.H.R.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Queensland University of Technology and the Centre for a Waste-Free World through Circular Economy Funding Support 2023.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the Queensland University of Technology and the Centre for a Waste-Free World for providing financial support in carrying out this research.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Pegna, J. Exploratory investigation of solid freeform construction. *Constr. Build. Mater.* **1997**, *5*, 427–437. [CrossRef]
2. Nguyen-Van, V.; Panda, B.; Zhang, G.; Nguyen-Xuan, H.; Tran, P. Digital design computing and modelling for 3-D concrete printing. *Constr. Build. Mater.* **2021**, *123*, 103529. [CrossRef]
3. Mandal, R.; Panda, S.K.; Nayak, S. Rheology of Concrete: Critical Review, recent advancements, and future prospectives. *Constr. Build. Mater.* **2023**, *392*, 132007. [CrossRef]
4. Xiao, J.; Ji, G.; Zhang, Y.; Ma, G.; Mechtcherine, V.; Pan, J.; Wang, L.; Ding, T.; Duan, Z.; Du, S. Large-scale 3D printing concrete technology: Current status and future opportunities. *Cem. Concr. Compos.* **2021**, *122*, 104115. [CrossRef]
5. Shakor, P.; Nejadi, S.; Paul, G. An investigation into the behaviour of cementitious mortar in the construction of 3D printed members by the means of extrusion printing. In Proceedings of the 1st International Conference on 3D Construction Printing, Melbourne, VIC, Australia, 26–28 November 2018.
6. Mohan, M.K.; Rahul, A.; De Schutter, G.; Van Tittelboom, K. Extrusion-based concrete 3D printing from a material perspective: A state-of-the-art review. *Cem. Concr. Compos.* **2021**, *115*, 103855. [CrossRef]
7. Available online: https://www.maximizemarketresearch.com/wp-content/uploads/2019/04/3D-Concrete-Printing-Market.webp (accessed on 27 November 2023).
8. Mechtcherine, V.; Bos, F.P.; Perrot, A.; Da Silva, W.L.; Nerella, V.N.; Fataei, S.; Wolfs, R.J.; Sonebi, M.; Roussel, N. Extrusion-based additive manufacturing with cement-based materials—Production steps, processes, and their underlying physics: A review. *Cem. Concr. Res.* **2020**, *132*, 106037. [CrossRef]
9. Baz, B.; Aouad, G.; Remond, S. Effect of the printing method and mortar's workability on pull-out strength of 3D printed elements. *Constr. Build. Mater.* **2020**, *230*, 117002. [CrossRef]
10. Zhang, X.; Li, G.; Song, Z. Influence of styrene-acrylic copolymer latex on the mechanical properties and microstructure of Portland cement/Calcium aluminate cement/Gypsum cementitious mortar. *Constr. Build. Mater.* **2019**, *227*, 116666. [CrossRef]
11. Paul, S.C.; Tay, Y.W.D.; Panda, B.; Tan, M.J. Fresh and hardened properties of 3D printable cementitious materials for building and construction. *Arch. Civ. Mech. Eng.* **2018**, *18*, 311–319. [CrossRef]
12. Perrot, A.; Rangeard, D.; Pierre, A. Structural built-up of cement-based materials used for 3D-printing extrusion techniques. *Mater. Struct.* **2016**, *49*, 1213–1220. [CrossRef]
13. Shakor, P.; Nejadi, S.; Paul, G. A Study into the Effect of Different Nozzles Shapes and Fibre-Reinforcement in 3D Printed Mortar. *Materials* **2019**, *12*, 1708. [CrossRef]
14. Jiao, D.; Shi, C.; Yuan, Q.; An, X.; Liu, Y.; Li, H. Effect of constituents on rheological properties of fresh concrete-a review. *Cem. Concr. Compos.* **2017**, *83*, 146–159. [CrossRef]
15. Le, H.T.; Kraus, M.; Siewert, K.; Ludwig, H.-M. Effect of macro-mesoporous rice husk ash on rheological properties of mortar formulated from self-compacting high performance concrete. *Constr. Build. Mater.* **2015**, *80*, 225–235. [CrossRef]
16. Subramanian, N. Rheological Properties of Concrete. Available online: https://www.structuremag.org/?p=16960 (accessed on 10 February 2023).
17. Wang, L.; Ma, H.; Li, Z.; Ma, G.; Guan, J. Cementitious composites blending with high belite sulfoaluminate and medium-heat Portland cements for largescale 3D printing. *Addit. Manuf.* **2021**, *46*, 102189. [CrossRef]

18. Kondepudi, K.; Subramaniam, K.V.L. Formulation of alkali-activated fly ash-slag binders for 3D concrete printing. *Cem. Concr. Compos.* **2021**, *119*, 103983. [CrossRef]
19. Ahmed, W.; Alnajjar, F.; Zaneldin, E.; Al-Marzouqi, A.H.; Gochoo, M.; Khalid, S. Implementing FDM 3D printing strategies using natural fibers to produce biomass composite. *Materials* **2020**, *13*, 4065. [CrossRef]
20. Muthukrishnan, S.; Ramakrishnan, S.; Sanjayan, J. Technologies for improving buildability in 3D concrete printing. *Cem. Concr. Compos.* **2021**, *122*, 104144. [CrossRef]
21. Jindal, B.B.; Sharma, R. The effect of nanomaterials on properties of geopolymers derived from industrial by-products: A state-of-the-art review. *Constr. Build. Mater.* **2020**, *252*, 119028. [CrossRef]
22. Bos, F.; Wolfs, R.; Ahmed, Z.; Salet, T. Additive manufacturing of concrete in construction: Potentials and challenges of 3D concrete printing. *Virtual Phys. Prototypes* **2016**, *11*, 209–225. [CrossRef]
23. Tu, H.; Wei, Z.; Bahrami, A.; Kahla, N.B.; Ahmad, A.; Ozkılıç, Y.O. Recent advancements and future trends in 3D concrete printing using waste materials. *Dev. Built Environ.* **2023**, *16*, 100187. [CrossRef]
24. Buswell, R.A. 3D printing using concrete extrusion: A roadmap for research. *Cem. Concr. Res.* **2018**, *37–49*, 112. [CrossRef]
25. Ahari, R.S.; Erdem, T.K.; Ramyar, K. Thixotropy and structural breakdown properties of self consolidating concrete containing various supplementary cementitious materials. *Cem. Concr. Compos.* **2015**, *59*, 26–37. [CrossRef]
26. Ahari, R.S.; Erdem, T.K.; Ramyar, K. Effect of various supplementary cementitious materials on rheological properties of self-consolidating concrete. *Constr. Build. Mater.* **2015**, *75*, 89–98. [CrossRef]
27. Tran, T.N.; Bayer, I.S.; Heredia-Guerrero, J.A.; Frugone, M.; Lagomarsino, M.; Maggio, F.; Athanassiou, A. Cocoa shell waste biofilaments for 3D printing applications. *Macromol. Mater. Eng.* **2017**, *302*, 1700219. [CrossRef]
28. Wang, Q.; Sun, J.; Yao, Q.; Ji, C.; Liu, J.; Zhu, Q. 3D printing with cellulose materials. *Cellulose* **2018**, *25*, 4275–4301. [CrossRef]
29. Girdis, J.; Gaudion, L.; Proust, G.; Löschke, S.; Dong, A. Rethinking timber: Investigation into the use of waste macadamia nut shells for additive manufacturing. *JOM* **2017**, *69*, 575–579. [CrossRef]
30. Ahmad, M.N.; Wahid, M.K.; Maidin, N.A.; Ab Rahman, M.A.H.; Osman, M.H.; Alis, I.F. Mechanical characteristics of oil palm fiber reinforced thermoplastics as filament for fused deposition modeling (FDM). *Adv. Manuf.* **2020**, *8*, 72–81. [CrossRef]
31. Xie, G.; Zhang, Y.; Lin, R. Plasticizer combinations and performance of wood flour–poly (lactic acid) 3D printing filaments. *Bio Resour.* **2017**, *12*, 6736–6748. [CrossRef]
32. Nguyen, N.A.; Barnes, S.H.; Bowland, C.C.; Meek, K.M.; Littrell, K.C.; Keum, J.K.; Naskar, A.K. A path for lignin valorization via additive manufacturing of high-performance sustainable composites with enhanced 3D printability. *Sci. Adv.* **2015**, *4*, eaat4967. [CrossRef]
33. Kariz, M.; Sernek, M.; Obu'cina, M.; Kuzman, M.K. Effect of wood content in FDM filament on properties of 3D printed parts. *Mater. Today Commun.* **2018**, *14*, 135–140. [CrossRef]
34. Le Duigou, A.; Barbé, A.; Guillou, E.; Castro, M. 3D printing of continuous flax fibre reinforced biocomposites for structural applications. *Mater. Des.* **2020**, *180*, 107884. [CrossRef]
35. Nida, S.; Anukiruthika, T.; Moses, J.A.; Anandharamakrishnan, C. 3D printing of grinding and milling fractions of rice husk. *Waste Biomass Valorization* **2021**, *12*, 81–90. [CrossRef]
36. Neville, A.M.; Brooks, J.J. *Concrete Technology*, 3rd ed.; Pearson Education: London, UK, 2008.
37. Kanamarlapudi, L.; Jonalagadda, K.B.; Jagarapu, D.C.K.; Eluru, A. Different mineral admixtures in concrete: A review. *SN Appl. Sci.* **2020**, *2*, 760. [CrossRef]
38. Selvaranjan, K.; Navaratnam, S.; Gamage, J.; Thamboo, J.; Siddique, R. Thermal and environmental impact analysis of rice husk ash-based mortar as insulating wall plaster. *Constr. Build. Mater.* **2022**, *283*, 122744. [CrossRef]
39. Selvaranjan, K.; Gamage, J.; De Silva, G.I.; Navaratnam, S. Development of sustainable mortar using waste rice husk ash from rice mill plant: Physical and thermal properties. *J. Build. Eng.* **2022**, *43*, 102614. [CrossRef]
40. Chen, Y.; He, S.; Zhang, Y.; Wan, Z.; Çopuroğlu, O.; Schlangen, E. 3D printing of calcined clay-limestone-based cementitious materials. *Cem. Concr. Res.* **2021**, *149*, 106553. [CrossRef]
41. Chen, Y.; Li, Z.; Figueiredo, S.C.; Çopuroğlu, O.; Veer, F.; Schlangen, E. Limestone and calcined clay-based sustainable cementitious materials for 3D concrete printing: A fundamental study of extrudability and early-age strength development. *Appl. Sci.* **2019**, *9*, 9091809. [CrossRef]
42. Long, W.J.; Lin, C.; Tao, J.L.; Ye, T.H.; Fang, Y. Printability and particle packing of 3D-printable limestone calcined clay cement composites. *Constr. Build. Mater.* **2021**, *282*, 647. [CrossRef]
43. de Matos, P.R.; Zat, T.; Lima, M.M.; Neto, J.D.; Souza, M.T.; Rodríguez, E.D. Effect of the superplasticizer addition time on the fresh properties of 3D printed limestone calcined clay cement (LC3) concrete. *Case Stud. Constr. Mater.* **2023**, *19*, e02419. [CrossRef]
44. Chen, Y.; Chaves Figueiredo, S.; Yalçinkaya, Ç.; Çopuroğlu, O.; Veer, F.; Schlangen, E. The effect of viscosity-modifying admixture on the extrudability of limestone and calcined clay-based cementitious material for extrusion-based 3D concrete printing. *Materials* **2019**, *12*, 1374. [CrossRef]
45. Agustí-Juan, I.; Müller, F.; Hack, N.; Wangler, T.; Habert, G. Potential benefits of digital fabrication for complex structures: Environmental assessment of a robotically fabricated concrete wall. *J. Clean. Prod.* **2017**, *154*, 330–340. [CrossRef]
46. Weng, Y.; Li, M.; Ruan, S.; Wong, T.N.; Tan, M.J.; Yeong, K.L.; Qian, S. Comparative economic, environmental and productivity assessment of a concrete bathroom unit fabricated through 3D printing and a precast approach. *J. Clean. Prod.* **2020**, *261*, 121245. [CrossRef]

47. Chen, M.; Cheng, X. Rheological parameters, thixotropy and creep of 3D-Printing calcium sulfoaluminate cement composites modified by bentonite. *Compos. Part B Eng.* **2020**, *186*, 107821. [CrossRef]
48. Khalil, N.; Aouad, G.; El Cheikh, K.; Rémond, S. Use of calcium sulfoaluminate cements for setting control of 3D-printing mortars. *Constr. Build. Mater.* **2017**, *157*, 382–391. [CrossRef]
49. Liao, Y.; Wang, S.; Wang, K.; Al Qunaynah, S.; Wan, S.; Yuan, Z.; Xu, P.; Tang, S. A study on the hydration of calcium aluminate cement pastes containing silica fume using non-contact electrical resistivity measurement. *J. Mater. Res. Technol.* **2023**, *24*, 8135–8149. [CrossRef]
50. *ASTM C618-08*; Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. ASTM International: West Conshohocken, PA, USA, 2008.
51. Saad, S.A.; Nuruddin, M.F.; Shafiq, N.; Ali, M. Pozzolanic reaction mechanism of rice husk ash in concrete—A Review. *Appl. Mech. Mater.* **2015**, *773*, 1143–1147. [CrossRef]
52. Abdullah, M.A.; Gamage, J. Behaviour of Concrete Produced with Cement and Rice Husk Ash. In Proceedings of the 6th International Conference on Structural Engineering and Construction Management 2015, Kandy, Sri Lanka, 11 December 2015; p. 176.
53. Srikanth, G.; Fernando, A.; Selvaranjan, K.; Gamage, J.; Ekanayake, L. Development of a plastering mortar using waste bagasse and rice husk ashes with sound mechanical and thermal properties. *Case Stud. Constr. Mater.* **2022**, *16*, e00956. [CrossRef]
54. Jesus, M.; Teixeira, J.; Alves, J.L.; Pessoa, S.; Guimarães, A.S.; Rangel, B. Potential Use of Sugarcane Bagasse Ash in Cementitious Mortars for 3D Printing. In *Materials Design and Applications IV*; Springer: Cham, Switzerland, 2022; pp. 89–103.
55. Wang, L.; Jin, M.; Zhou, S.; Tang, S.; Lu, X. Investigation of microstructure of C-S-H and micro-mechanics of cement pastes under NH_4NO_3 dissolution by 29Si MAS NMR and microhardness. *Measurement* **2021**, *185*, 110019. [CrossRef]
56. Geng, Z.; Tang, S.; Wang, Y.; He, Z.; Wu, K. Stress relaxation properties of calcium silicate hydrate: A molecular dynamics study. *J. Zhejiang Univ. -Sci. A* **2024**, *25*, 97–115. [CrossRef]
57. Wang, L.; Guo, F.; Lin, Y.; Yang, H.; Tang, S.W. Comparison between the effects of phosphorous slag and fly ash on the C-S-H structure, long-term hydration heat and volume deformation of cement-based materials. *Constr. Build. Mater.* **2020**, *250*, 118807. [CrossRef]
58. Pimentel Tinoco, M.; Gouvêa, L.; de Cássia Magalhães Martins, K.; Dias Toledo Filho, R.; Aurelio Mendoza Reales, O. The use of rice husk particles to adjust the rheological properties of 3D printable cementitious composites through water sorption. *Constr. Build. Mater.* **2023**, *365*, 130046. [CrossRef]
59. Celik, F.; Canakci, H. An investigation of rheological properties of cement-based grout mixed with rice husk ash (RHA). *Constr. Build. Mater.* **2015**, *91*, 187–194. [CrossRef]
60. Guo, A.; Sun, Z.; Qi, C.; Sathitsuksanoh, N. Hydration of portland cement pastes containing untreated and treated hemp powders. *J. Mater. Civ. Eng.* **2020**, *32*, 04020148. [CrossRef]
61. Morrision, F.A. *Understanding Rheology*; Oxford University Press: New York, NY, USA, 2001.
62. Muthukrishnan, S.; Kua, H.W.; Yu, L.N.; Chung, J.K. Fresh Properties of Cementitious Materials Containing Rice Husk Ash for Construction 3D Printing. *J. Mater. Civ. Eng.* **2020**, *32*, 04020195. [CrossRef]
63. Samad, N.A.I.A.; Abdullah, S.R.; Ibrahim, M.; Shahidan, S.; Ismail, N. Initial properties of 3D printing concrete using Rice Husk Ash (RHA) as Partial Cement Replacement. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1022*, 12055. [CrossRef]
64. Sirivivatnanon, V.; Ho, D.W.S.; Baweja, D. *The Role of Supplementary Cementitious Materials in Australian Concrete Construction Practice*; Supplementary Cementitious Materials in Concrete, a Practical Seminar on the Specification, Use and Performance of Ground Granulated Blast Furnace Slag, Fly Ash and Condensed Silica Fume; Concrete, Cement and Concrete Association: Perth, Australia, 1991; pp. 2–9. ISBN 0947 132 47 3.
65. *AS 3582.1-1998*; Supplementary Cementitious Materials for Use with Portland and Blended Cement Fly Ash. Standards Australia: Sydney, NSW, Australia, 1998.
66. *AS 3583.6-1995*; Methods of Test for Supplementary Cementitious Materials for Use with Portland Cement—Determination of Relative Water Requirement and Relative Strength. Standards Australia: Sydney, NSW, Australia, 1995.
67. Kovler, K. Does the utilization of coal fly ash in concrete construction present a radiation hazard? *Constr. Build. Mater.* **2012**, *29*, 158–166. [CrossRef]
68. Nath, P.; Sarker, P. Effect of fly ash on the durability properties of high strength concrete. *Procedia Eng.* **2011**, *14*, 1149–1156. [CrossRef]
69. Yao, Z.T.; Ji, X.S.; Sarker, P.K.; Tang, J.H.; Ge, L.Q.; Xia, M.S.; Xi, Y.Q. A comprehensive review on the applications of coal fly ash. *Earth-Sci. Rev.* **2015**, *141*, 105–121. [CrossRef]
70. Topçu, I.B.; Canbaz, M. Effect of different fibers on the mechanical properties of concrete containing fly ash. *Constr. Build. Mater.* **2007**, *21*, 1486–1491. [CrossRef]
71. Wang, L.; Zhou, S.; Shi, Y.; Huang, Y.; Zhao, F.; Huo, T.; Tang, S. The Influence of Fly Ash Dosages on the Permeability, Pore Structure and Fractal Features of Face Slab Concrete. *Fractal Fract.* **2022**, *6*, 476. [CrossRef]
72. Peled, A.; Shah, S.P. Processing effects in cementitious composites: Extrusion and casting. *J. Mater. Civ. Eng.* **2003**, *1561*, 192–199. [CrossRef]
73. Chen, Y.; Figueiredo, S.C.; Li, Z.; Chang, Z.; Jansen, K.; Çopuroğlu, O.; Schlangen, E. Improving printability of limestone-calcined clay-based cementitious materials by using viscosity-modifying admixture. *Cem. Concr. Res.* **2020**, *132*, 106040. [CrossRef]

74. Figueiredo, S.C.; Çopuroğlu, O.; Schlangen, E. Effect of viscosity modifier admixture on Portland cement paste hydration and microstructure. *Constr. Build. Mater.* **2019**, *212*, 818–840. [CrossRef]
75. Reiter, L.; Wangler, T.; Roussel, N.; Flatt, R.J. The role of early age structural buildup in digital fabrication with concrete. *Cem. Concr. Res.* **2018**, *112*, 86–95. [CrossRef]
76. Ruslan, I.; Ruslan, B.; Evgenij, K. The effect of metal and polypropylene fiber on technological and physical mechanical properties of activated cement compositions. *Case Stud. Constr. Mater.* **2022**, *16*, e00882. [CrossRef]
77. Souza, M.T.; Ferreira, I.M.; de Moraes, E.G.; Senff, L.; de Oliveira, A.P. 3D printed concrete for large-scale buildings: An overview of rheology, printing parameters, chemical admixtures, reinforcements, and economic and environmental prospects. *J. Build. Eng.* **2020**, *32*, 101833. [CrossRef]
78. Liu, J.; Yu, C.; Shu, X.; Ran, Q.; Yang, Y. Recent advance of chemical admixtures in concrete. *Cem. Concr. Res.* **2019**, *124*, 105834. [CrossRef]
79. Roussel, N.; Ovarlez, G.; Garrault, S.; Brumaud, C. The origins of thixotropy of fresh cement pastes. *Cem. Concr. Res.* **2012**, *42*, 148–157. [CrossRef]
80. Tang, S.W.; Cai, R.J.; He, Z.; Cai, X.H.; Shao, H.Y.; Li, Z.J.; Yang, H.M.; Chen, E. Continuous Microstructural Correlation of Slag/Superplasticizer cement pastes by heat and impedance methods via fractal analysis. *Fractals* **2017**, *25*, 1740003. [CrossRef]
81. Kujawa, W.; Olewnik-Kruszkowska, E.; Nowaczyk, J. Concrete Strengthening by Introdusing Polymer-Based Additives into the Cement Matrix—A Mini Review. *Materials* **2021**, *14*, 6071. [CrossRef]
82. Ahmed, G.H. A review of 3D concrete printing: Materials and process characterization, economic considerations and environmental sustainability. *J. Build. Eng.* **2023**, *66*, 105863. [CrossRef]
83. Collepardi, M. Admixtures used to enhance placing characteristics of concrete. *Cem. Concr. Compos.* **1998**, *20*, 103–112. [CrossRef]
84. Al-Neshawy, F.; Ojala, T.; Punkki, J. Stability of Air Content in Fresh Concretes with PCE-Based Superplasticizers. *Nord. Concr. Res.* **2019**, *60*, 145–158. [CrossRef]
85. Abd, M.; Abd, S.; Heikal, M.; El Didamony, H. Hydration and durability of sulphateresisting and slag cement blends in Caron's Lake water. *Cem. Concr. Res.* **2005**, *35*, 1592–1600.
86. Breilly, D.; Fadlallah, S.; Froidevaux, V.; Colas, A.; Allais, F. Origin and industrial applications of lignosulfonates with a focus on their use as superplasticizers in concrete. *Constr. Build. Mater.* **2021**, *301*, 124065. [CrossRef]
87. Gelardi, G.; Flatt, R. Working mechanisms of water reducers and superplasticizers. In *Science and Technology of Concrete Admixtures*; Elsevier: New York, NY, USA, 2016; pp. 257–278.
88. Marchon, D.; Kawashima, S.; Bessaies-Bey, H.; Mantellato, S.; Ng, S. Hydration and rheology control of concrete for digital fabrication: Potential admixtures and cement chemistry. *Cem. Concr. Res.* **2018**, *112*, 96–110. [CrossRef]
89. Dalas, F.; Pourchet, S.; Rinaldi, D.; Nonat, A.; Sabio, S.; Mosquet, M. Modification of the rate of formation and surface area of ettringite by polycarboxylate ether superplasticizers during early C3A-CaSO4 hydration. *Cem. Concr. Res.* **2015**, *69*, 105–113. [CrossRef]
90. Benaicha, M.; Hafidi Alaoui, A.; Jalbaud, O.; Burtschell, Y. Dosage effect of superplasticizer on self-compacting concrete: Correlation between rheology and strength. *J. Mater. Res. Technol.* **2019**, *8*, 2063–2069. [CrossRef]
91. Rath, S.; Ouchi, M. Effective Mixing Method for Stability of Air Content in Fresh Mortar of Self-Compacting Concrete in Terms of Air Diameter. *Internet J. Soc. Soc. Manag. Syst.* **2015**, *10*, sms15-6550.
92. Ma, B.; Ma, M.; Shen, X.; Li, X.; Wu, X. Compatibility between a polycarboxylate superplasticizer and the belite-rich sulfoaluminate cement: Setting time and the hydration properties. *Constr. Build. Mater.* **2014**, *51*, 47–54. [CrossRef]
93. Zhu, W.; Feng, Q.; Luo, Q.; Bai, X.; Lin, X.; Zhang, Z. Effects of -PCE on the dispersion of cement particles and initial hydration. *Materials* **2021**, *14*, 3195. [CrossRef] [PubMed]
94. Dalas, F.; Nonat, A.; Pourchet, S.; Mosquet, M.; Rinaldi, D.; Sabio, S. Tailoring the anionic function and the side chains of comb-like superplasticizers to improve their adsorption. *Cem. Concr. Res.* **2015**, *67*, 21–30. [CrossRef]
95. Sebök, T.; Stráňel, O. Relationships between the properties of ligninsulphonates and parameters of modified samples with cement binders. *Cem. Concr. Res.* **2000**, *30*, 511–515. [CrossRef]
96. Taylor, H.F.W. *Cement Chemistry*, 2nd ed.; Thomas Telford: London, UK, 1997.
97. Chen, Y.; Chang, Z.; He, S.; Çopuroğlu, O.; Šavija, B.; Schlangen, E. Effect of curing methods during a long time gap between two printing sessions on the interlayer bonding of 3D printed cementitious materials. *Constr. Build. Mater.* **2022**, *332*, 127394. [CrossRef]
98. Le, T.T.; Austin, S.A.; Lim, S.; Buswell, R.A.; Gibb, A.G.; Thorpe, T. Mix design and fresh properties for high-performance printing concrete. *Mater. Struct.* **2012**, *45*, 1221–1232. [CrossRef]
99. Melichar, J.; Žižková, N.; Brožovský, J.; Mészárosová, L.; Hermann, R. Study of the Interaction of Cement-Based Materials for 3D Printing with Fly Ash and Superabsorbent Polymers. *Buildings* **2022**, *12*, 2008. [CrossRef]
100. Sun, X.; Zhou, J.; Wang, Q.; Shi, J.; Wang, H. PVA fibre reinforced high-strength cementitious composite for 3D printing: Mechanical properties and durability. *Addit. Manuf.* **2022**, *49*, 102500. [CrossRef]
101. Roussel, N.; Lemaître, A.; Flatt, R.J.; Coussot, P. Steady state flow of cement suspensions: A micromechanical state of the art. *Cem. Concr. Res.* **2010**, *40*, 77–84. [CrossRef]
102. Marchon, D.; Juilland, P.; Gallucci, E.; Frunz, L.; Flatt, R.J. Molecular and submolecular scale effects of comb-copolymers on tri-calcium silicate reactivity: Toward molecular design. *J. Am. Ceram. Soc.* **2017**, *100*, 817–841. [CrossRef]

103. Palacios, M.; Flatt, R. Working mechanism of viscosity modifying admixtures. In *Science and Technology of Concrete Admixtures*; Elsevier: New York, NY, USA, 2016; pp. 415–432.
104. Dvorkin, L.; Konkol, J.; Marchuk, V.; Huts, A. Effectiveness of Polymer Additives in Concrete for 3D Concrete Printing Using Fly Ash. *Polymers* **2022**, *14*, 5467. [CrossRef]
105. Bessaies-Bey, H.; Baumann, R.; Schmitz, M.; Radler, M.; Roussel, N. Effect of polyacrylamide on rheology of fresh cement pastes. *Cem. Concr. Res.* **2015**, *76*, 98–106. [CrossRef]
106. Van Olphen, H.; Hsu, P.H. An introduction to clay colloid chemistry. *Soil Sci.* **1978**, *126*, 59. [CrossRef]
107. Liu, C.; Wang, X.; Chen, Y.; Zhang, C.; Ma, L.; Deng, Z.; Chen, C.; Zhang, Y.; Pan, J.; Banthia, N. Influence of hydroxypropyl methylcellulose and silica fume on stability, rheological properties, and printability of 3D printing foam concrete. *Cem. Concr. Compos.* **2021**, *122*, 104158. [CrossRef]
108. Palaniappan, M. An optimal utilization of waste materials in concrete to enhance the strength property: An experimental approach and possibility of 3D printing technology. In *Sustainability for 3D Printing*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 149–158.
109. Chen, M.; Yang, L.; Zheng, Y.; Li, L.; Wang, S.; Huang, Y.; Zhao, P.; Lu, L.; Cheng, X. Rheological behaviors and structure build-up of 3D printed polypropylene and polyvinyl alcohol fiber-reinforced calcium sulphoaluminate cement composites. *J. Mater. Res. Technol.* **2021**, *10*, 1402–1414. [CrossRef]
110. Zhang, Y.; Aslani, F. Development of fibre reinforced engineered cementitious composite using polyvinyl alcohol fibre and activated carbon powder for 3D concrete printing. *Constr. Build. Mater.* **2021**, *303*, 124453. [CrossRef]
111. Afroughsabet, V.; Ozbakkaloglu, T. Mechanical and durability properties of high-strength concrete containing steel and polypropylene fibers. *Constr. Build. Mater.* **2015**, *94*, 73–82. [CrossRef]
112. Sun, Z.; Xu, Q. Microscopic, physical and mechanical analysis of polypropylene fiber reinforced concrete. *Mater. Sci. Eng. A* **2009**, *527*, 198–204. [CrossRef]
113. Ramezanianpour, A.A.; Esmaeili, M.; Ghahari, S.A.; Najafi, M.H. Laboratory study on the effect of polypropylene fiber on durability, and physical and mechanical characteristic of concrete for application in sleepers. *Constr. Build. Mater.* **2013**, *44*, 411–418. [CrossRef]
114. Kim, J.H.J.; Park, C.G.; Lee, S.W.; Lee, S.W.; Won, J.P. Effects of the geometry of recycled PET fiber reinforcement on shrinkage cracking of cement-based composites. *Compos. Part B Eng.* **2008**, *39*, 442–450. [CrossRef]
115. Mardani-aghabaglou, A.; Metin, I.; Özen, S. The effect of shrinkage reducing admixture and polypropylene fibers on drying shrinkage behaviour of concrete. *Cem. Wapno Beton* **2019**, *3*, 227–237. [CrossRef]
116. Hambach, M.; Volkmer, D. Properties of 3D-printed fiber-reinforced Portland cement paste. *Cem. Concr. Compos.* **2017**, *79*, 62–70. [CrossRef]
117. Yang, Y.; Wu, C.; Liu, Z.; Wang, H.; Ren, Q. Mechanical anisotropy of ultra-high performance fibre-reinforced concrete for 3D printing. *Cem. Concr. Compos.* **2022**, *125*, 104310. [CrossRef]
118. Singh, A.; Liu, Q.; Xiao, J.; Lyu, Q. Mechanical and macrostructural properties of 3D printed concrete dosed with steel fibers under different loading direction. *Constr. Build. Mater.* **2022**, *323*, 126616. [CrossRef]
119. Bos, F.; Bosco, E.; Salet, T. Ductility of 3D printed concrete reinforced with short straight steel fibers. *Virtual Phys. Prototyp.* **2019**, *14*, 160–174. [CrossRef]
120. Li, L.; Xiao, B.; Fang, Z.; Xiong, Z.; Chu, S.; Kwan, A. Feasibility of glass/basalt fiber reinforced seawater coral sand mortar for 3D printing. *Addit. Manuf.* **2021**, *37*, 101684. [CrossRef]
121. Xiao, J.; Zou, S.; Ding, T.; Duan, Z.; Liu, Q. Fiber-reinforced mortar with 100% recycled fine aggregates: A cleaner perspective on 3D printing. *J. Clean. Prod.* **2021**, *319*, 128720. [CrossRef]
122. Lura, P.; Pease, B.; Mazzotta, G.B.; Rajabipour, F.; Weiss, J. Influence of Shrinkage-Reducing Admixtures on Development of Plastic Shrinkage Cracks. *ACI Mater. J.* **2007**, *104*, 187.
123. Sun, J.; Aslani, F.; Lu, J.; Wang, L.; Huang, Y.; Ma, G. Fibre-reinforced lightweight engineered cementitious composites for 3D concrete printing. *Ceram. Int.* **2021**, *47*, 27107–27121. [CrossRef]
124. Teixeira, R.S.; Santos, S.F.d.; Christoforo, A.L.; Savastano, H., Jr.; Lahr, F.A.R. Extrudability of cement-based composites reinforced with curauá (*Ananas erectifolius*) or polypropylene fibers. *Constr. Build. Mater.* **2019**, *205*, 97–110. [CrossRef]
125. Ward, C.R.; French, D.; Jankowski, J.; Dubikova, M.; Li, Z.; Riley, K.W. Element mobility from fresh and long-stored acidic fly ashes associated with an Australian power station. *Int. J. Coal Geol.* **2009**, *80*, 224–236. [CrossRef]
126. Zhang, Y.; Jiang, Z.; Zhu, Y.; Zhang, J.; Ren, Q.; Huang, T. Effects of redispersible polymer powders on the structural build-up of 3D printing cement paste with and without hydroxypropyl methylcellulose. *Constr. Build. Mater.* **2021**, *267*, 120551. [CrossRef]
127. Arwar, W.; Ghafor, K.; Mohammed, A. Regression analysis and Vipulanandan model to quantify the effect of polymers on the plastic and hardened properties with the tensile bonding strength of the cement mortar. *Results Mater.* **2019**, *1*, 100011.
128. Li, L.; Wang, R.; Lu, Q. Influence of polymer latex on the setting time, mechanical properties and durability of calcium sulfoaluminate cement mortar. *Constr. Build. Mater.* **2018**, *169*, 911–922. [CrossRef]
129. Medeiros, M.H.F.; Helene, P.; Selmo, S. Influence of EVA and acrylate polymers on some mechanical properties of cementitious repair mortars. *Constr. Build. Mater.* **2009**, *23*, 2527–2533. [CrossRef]
130. Krishnaraja, A.R.; Guru, K.V. 3D Printing Concrete: A Review. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1055*, 012033. [CrossRef]
131. Grzeszczyk, S.; Matuszek-Chmurowska, A. Microstructure of reactive powder concrete. *Cem. Wapno Beton* **2018**, *1*, 1–15.

132. Li, Y.; Zhang, H.; Huang, M.; Yin, H.; Jiang, K.; Xiao, K.; Tang, S. Influence of Different Alkali Sulfates on the Shrinkage, Hydration, Pore Structure, Fractal Dimension and Microstructure of Low-Heat Portland Cement, Medium-Heat Portland Cement and Ordinary Portland Cement. *Fractal Fract.* **2021**, *5*, 79. [CrossRef]
133. Pham, L.; Tran, P.; Sanjayan, J. Steel fibres reinforced 3D printed concrete: Influence of fibre sizes on mechanical performance. *Constr. Build. Mater.* **2020**, *250*, 118785. [CrossRef]
134. Ding, T.; Xiao, J.; Zou, S.; Yu, J. Flexural properties of 3D printed fibre-reinforced concrete with recycled sand. *Constr. Build. Mater.* **2021**, *288*, 123077. [CrossRef]
135. van den Heever, M.; du Plessis, A.; Kruger, J.; van Zijl, G. Evaluating the effects of porosity on the mechanical properties of extrusion-based 3D printed concrete. *Cem. Concr. Res.* **2022**, *153*, 106695. [CrossRef]
136. Chu, S.; Li, L.; Kwan, A. Development of extrudable high strength fiber reinforced concrete incorporating nano calcium carbonate. *Addit. Manuf.* **2021**, *37*, 101617. [CrossRef]
137. Rahul, A.V.; Santhanam, M.; Meena, H.; Ghani, Z. 3D printable concrete: Mixture design and test methods. *Cem. Concr. Compos.* **2019**, *97*, 13–23. [CrossRef]
138. Liu, G.; Cheng, W.; Chen, L.; Pan, G.; Liu, Z. Rheological properties of fresh concrete and its application on shotcrete. *Constr. Build. Mater.* **2020**, *243*, 118180. [CrossRef]
139. *T/CECS 786-2020*; China Association for Engineering Construction Standardization, Technical Specification for Concrete 3D Printing. China Planning Press: Beijing, China, 2020.
140. Mohan, M.K.; Rahul, A.V.; Van Tittelboom, K.; De Schutter, G. Rheological and pumping behaviour of 3D printable cementitious materials with varying aggregate content. *Cem. Concr. Res.* **2021**, *139*, 106258. [CrossRef]
141. Panda, B. Anisotropic mechanical performance of 3d printed fiber reinforced sustainable construction material. *Mater. Lett.* **2017**, *209*, 146–149. [CrossRef]
142. Kazemian, A.; Yuan, X.; Cochran, E.; Khoshnevis, B. Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture. *Constr. Build. Mater.* **2017**, *145*, 639–647. [CrossRef]
143. Ma, G.; Wang, L. A critical review of preparation design and workability measurement of concrete material for largescale 3D printing. *Front. Struct. Civ. Eng.* **2018**, *12*, 382–400. [CrossRef]
144. Lv, J.; Du, Q.; Zhou, T.; He, Z.; Li, K. Fresh and mechanical properties of self compacting rubber lightweight aggregate concrete and corresponding mortar. *Adv. Mater. Sci. Eng.* **2019**, *2019*, 8372547. [CrossRef]
145. Senff, L.; Hotza, D.; Labrincha, J.A. Effect of lightweight aggregates addition on the rheological properties and hardened state of mortar. *Appl. Rheol.* **2011**, *21*, 13668.
146. Available online: https://www.abs.gov.au/statistics/understanding-statistics/guide-labour-statistics/industry-employment-guide (accessed on 31 October 2023).
147. Available online: https://www.afr.com/policy/economy/infrastructure-splurge-exacerbating-housing-shortage-rba-20231110-p5ej14 (accessed on 31 October 2023).
148. Available online: https://hia.com.au/our-industry/newsroom/economic-research-and%20forecasting/2022/07/shortage-of-building-trades-remains-acute (accessed on 31 October 2023).
149. Pan, Y.; Zhang, Y.; Zhang, D.; Song, Y. 3D printing in construction: State of the art and applications. *Int. J. Adv. Manuf. Technol.* **2021**, *115*, 1329–1348. [CrossRef]
150. Bazli, M.; Ashrafi, H.; Rajabipour, A.; Kutay, C. 3D printing for remote housing: Benefits and challenges. *Autom. Constr.* **2023**, *148*, 104772. [CrossRef]
151. Available online: https://www.theguardian.com/australia-news/2022/nov/03/remote-indigenous-community-pioneers-3d-printed-homes-set-to-change-rural-lives (accessed on 3 November 2023).
152. Ma, G.; Buswell, R.; da Silva, W.R.L.; Wang, L.; Xu, J.; Jones, S.Z. Technology readiness: A global snapshot of 3D concrete printing and the frontiers for development. *Cem. Concr. Res.* **2022**, *156*, 106774. [CrossRef]
153. Sakin, M.; Kiroglu, Y.C. 3D printing of buildings: Construction of the sustainable houses of the future by BIM. *Energy Procedia* **2017**, *134*, 702–7711. [CrossRef]
154. Alami, A.H.; Olabi, A.G.; Ayoub, M.; Aljaghoub, H.; Alasad, S.; Abdelkareem, M.A. 3D Concrete Printing: Recent Progress, Applications, Challenges, and Role in Achieving Sustainable Development Goals. *Buildings* **2023**, *13*, 924. [CrossRef]
155. Avrutis, D.; Nazari, A.; Sanjayan, J.G. Chapter 19—Industrial Adoption of 3D Concrete Printing in the Australian Market: Potentials and Challenges. In *3D Concrete Printing Technology*; Sanjayan, J.G., Nazari, A., Nematollahi, B., Eds.; Butterworth-Heinemann: Oxford, UK, 2019; pp. 389–409. ISBN 9780128154816.
156. El-Sayegh, S.; Romdhane, L.; Manjikian, S. A critical review of 3D printing in construction: Benefits, challenges, and risks. *Arch. Civ. Mech. Eng.* **2020**, *20*, 1–25. [CrossRef]
157. Tay YW, D.; Panda, B.; Paul, S.C.; Noor Mohamed, N.A.; Tan, M.J.; Leong, K.F. 3D printing trends in building and construction industry: A review. *Virtual Phys. Prototyp.* **2017**, *12*, 261–276. [CrossRef]
158. Ambily, P.; Kaliyavaradhan, S.K.; Rajendran, N. Top challenges to widespread 3D concrete printing (3DCP) adoption—A review. *Eur. J. Environ. Civ. Eng.* **2023**, *28*, 300–328. [CrossRef]
159. Shahzad, Q.; Umair, M.; Waqar, S. Bibliographic analysis on 3D printing in the building and construction industry: Printing systems, material properties, challenges, and future trends. *J. Sustain. Constr. Mater. Technol.* **2022**, *7*, 198–220. [CrossRef]

160. Available online: https://www.thebusinessresearchcompany.com/report/3d-printing-building-construction-market (accessed on 1 December 2023).
161. Zhang, J.; Wang, J.; Dong, S.; Yu, X.; Han, B. A review of the current progress and application of 3D printed concrete. *Compos. Part A Appl. Sci. Manuf.* **2019**, *125*, 105533. [CrossRef]
162. de Soto, B.G.; Agustí-Juan, I.; Hunhevicz, J.; Joss, S.; Graser, K.; Habert, G.; Adey, B.T. Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall. *Autom. Constr.* **2018**, *92*, 297–311. [CrossRef]
163. Batikha, M.; Jotangia, R.; Baaj, M.Y.; Mousleh, I. 3D concrete printing for sustainable and economical construction: A comparative study. *Autom. Constr.* **2022**, *134*, 104087. [CrossRef]
164. Jo, J.H.; Jo, B.W.; Cho, W.; Kim, J.-H. Development of a 3D Printer for Concrete Structures: Laboratory Testing of Cementitious Materials. *Int. J. Concr. Struct. Mater.* **2020**, *14*, 13. [CrossRef]
165. Siddika, A.; Al Mamun, A.; Ferdous, W.; Saha, A.K.; Alyousef, R. 3D-printed concrete: Applications, performance, and challenges. *J. Sustain. Cem. Mater.* **2019**, *9*, 127–164. [CrossRef]
166. *AS3600:2018 2020*; Australia Standards, Concrete Structures. Australia Standards: Sydney, NSW, Australia, 2020.
167. *AS3850.2:2015*; Australia Standards, Prefabricated Concrete Elements—Building Construction. Australia Standards: Sydney, NSW, Australia, 2015.
168. Bos, F.P.; Menna, C.; Pradena, M.; Kreiger, E.; da Silva, W.L.; Rehman, A.U.; Weger, D.; Wolfs, R.J.; Zhang, Y.; Ferrara, L.; et al. The realities of additively manufactured concrete structures in practice. *Cem. Concr. Res.* **2022**, *156*, 106746. [CrossRef]
169. *ISO/ASTM 52939:2023*; ASTM Standard, Additive Manufacturing for Construction Qualification Principles, Structural and Infrastructure Elements. International Organization for Standardization: Geneva, Switzerland, 2023.
170. *ACI Standards 564*; 3-D Printing with Cementitious Materials. American Concrete Institute: Farmington Hills, MI, USA.
171. *Technical Committee 276-DFC*; 276-DFC: Digital Fabrication with Cement-Based Materials, International Union of Laboratories and Experts in Construction Materials, Systems and Structures. RILEM: Champs-sur-Marne, France, 2016.
172. Gangotra, A.; Del Gado, E.; Lewis, J.I. 3D printing has untapped potential for climate mitigation in the cement sector. *Commun. Eng.* **2023**, *2*, 6. [CrossRef]
173. Available online: https://www.edb.gov.sg/en/our-industries/company-highlights/singapore-centre-for-3d-printing-sc3dp.html (accessed on 1 December 2023).
174. Advanced Manufacturing: A Roadmap for Unlocking Future Growth Opportunities for Australia CSIRO (November 2016). Available online: https://www.csiro.au/en/work-withus/industries/manufacturing/advanced-manufacturing-roadmap (accessed on 1 December 2023).
175. Available online: https://channellife.com.au/story/luyten-wins-funding-to-build-3d-houses-in-remote-australia#:~:text=Australian%203D%20printing%20technology%20company,durable%20housing%20across%20outback%20Australia (accessed on 1 December 2023).
176. Available online: https://dataportal.arc.gov.au/NCGP/Web/Grant/Grants#/1000/1//3D%20printing/ (accessed on 1 November 2023).
177. Available online: https://www.abc.net.au/news/2023-06-23/australia-housing-crisis-shortage-missing-homes-property-market/102515694 (accessed on 5 December 2023).
178. Available online: https://greenreview.com.au/product_news/lower-emission-3d-printing-technology-addresses-sectors-biggest-challenges/ (accessed on 4 December 2023).
179. Ding, T.; Xiao, J.; Zou, S.; Wang, Y. Hardened properties of layered 3D printed concrete with recycled sand. *Cem. Concr. Compos.* **2020**, *113*, 103724. [CrossRef]
180. Han, Y.; Yang, Z.; Ding, T.; Xiao, J. Environmental and economic assessment on 3D printed buildings with recycled concrete. *J. Clean. Prod.* **2021**, *278*, 123884. [CrossRef]
181. Luyten. Available online: https://www.luyten3d.com/ (accessed on 1 November 2023).
182. Contour3d. Available online: https://contour3d.com.au/ (accessed on 2 November 2023).
183. Fortex. Available online: https://fortexsolutions.com.au/ (accessed on 2 November 2023).
184. Macro3d. Available online: http://www.macro3d.com.au/ (accessed on 5 January 2024).
185. Khan, M.; McNally, C. A holistic review on the contribution of civil engineers for driving sustainable concrete construction in the built environment. *Dev. Built Environ.* **2023**, *16*, 100273. [CrossRef]
186. Du Plessis, A. Biomimicry for 3D concrete printing: A review and perspective. *Addit. Manuf.* **2021**, *38*, 101823. [CrossRef]
187. Sharma, R.; Jang, J.G.; Bansal, P.P. A comprehensive review on effects of mineral admixtures and fibers on engineering properties of ultra-high-performance concrete. *J. Build. Eng.* **2022**, *45*, 103314. [CrossRef]
188. Rejeski, D.; Zhao, D.; Huang, Y. Research needs and recommendations on environmental implications of additive manufacturing. *Addit. Manuf.* **2018**, *19*, 21–28. [CrossRef]
189. Lim, S.; Buswell, R.A.; Le, T.T.; Austin, S.A.; Gibb, A.G.; Thorpe, T. Developments in construction-scale additive manufacturing processes. *Autom. Constr.* **2012**, *21*, 262–268. [CrossRef]
190. Liang, F.; Liang, Y. Study on the status quo and problems of 3D printed buildings in China. *Glob. J. Hum. Soc. Sci.* **2014**, *14*, 7–10.
191. Federowicz, K.; Kaszyńska, M.; Zieliński, A.; Hoffmann, M. Effect of curing methods on shrinkage development in 3D-printed concrete. *Materials* **2020**, *13*, 2590. [CrossRef]

192. Fatih, O.; Halit, D.Y. Fresh and hardened properties of 3D high strength printing concrete and its recent application. *Iran. J. Sci. Technol.-Trans. Civ. Eng.* **2020**, *44*, 319–330.
193. Skibicki, S. Optimization of Cost of Building with Concrete Slabs Based on the Maturity Method. *IOP Conf. Ser. Mater. Sci. Eng.* **2017**, *245*, 22061. [CrossRef]
194. Ramezani, A.; Modaresi, S.; Dashti, P.; GivKashi, M.R.; Moodi, F.; Ramezanianpour, A.A. Effects of Different Types of Fibers on Fresh and Hardened Properties of Cement and Geopolymer-Based 3D Printed Mixtures: A Review. *Buildings* **2023**, *13*, 945. [CrossRef]
195. Nerella, V. Inline quantification of extrudability of cementitious materials for digital construction. *Cem. Concr. Compos.* **2019**, *95*, 260–270. [CrossRef]
196. Perrot, A.; Rangeard, D.; Melinge, Y.; Estelle, P.; Lanos, C. Extrusion criterion for firm cement-based materials. *Appl. Rheol.* **2009**, *19*, 53042. [CrossRef]
197. Khelifi, H.; Perrot, A.; Lecompte, T.; Rangeard, D.; Ausias, G. Prediction of extrusion load and liquid phase filtration during ram extrusion of high solid volume fraction pastes. *Powder Technol.* **2013**, *249*, 258–268. [CrossRef]
198. Chen, Y.; Struble, L.J.; Paulino, G.H. Extrudability of cement-based materials. *Am. Ceram. Soc. Bull.* **2006**, *85*, 9101–9105.
199. Perrot, A.; Rangeard, D.; Mélinge, Y. Prediction of the ram extrusion force of cement based materials. *Appl. Rheol.* **2014**, *24*, 53320. [CrossRef]
200. Perrot, A.; Rangeard, D.; Nerella, V.N.; Mechtcherine, V. Extrusion of cement—Based materials—An overview. *RILEM Tech. Lett.* **2019**, *3*, 91–97. [CrossRef]
201. Spangenberg, J.; Roussel, N.; Hattel, J.H.; Stang, H.; Skocek, J.; Geiker, M.R. Flow induced particle migration in fresh concrete: Theoretical frame, numerical simulations and experimental results on model fluids. *Cem. Concr. Res.* **2012**, *42*, 633–641. [CrossRef]
202. Browne, R.D.; Bamforth, P.B. Tests to establish concrete pumpability. *ACI Struct. J.* **1977**, *74*, 193–203.
203. Qingxuan, S.H.; Shengmu, W.A.; Qiuwei, W.A.; Yi, T.A.; Jian, H.U. Experimental investigations on the influence of nozzle travel speed and height on the mechanical properties of 3D printed concrete. *Acta Mater. Compos. Sin.* **2022**, *40*, 1–13. (In Chinese)
204. Panda, B.; Paul, S.C.; Mohamed, N.A.N.; Tay, Y.W.D.; Tan, M.J. Measurement of tensile bond strength of 3d printed geopolymer mortar. *Measurement* **2018**, *113*, 108–116. [CrossRef]
205. Yu, S.; Xia, M.; Sanjayan, J.; Yang, L.; Xiao, J.; Du, H. Microstructural characterization of 3D printed concrete. *J. Build. Eng.* **2021**, *44*, 102948. [CrossRef]
206. Liu, Z.; Wang, Z.; Wang, L.; Zhao, X. Interlayer bond strength of 3D printing cement paste by cross-bonded method. *J. Chin. Ceram. Soc.* **2019**, *47*, 648–652. (In Chinese)
207. Le, T.T.; Austin, S.A.; Lim, S. Hardened properties of high-performance printing concrete. *Cem. Concr. Res.* **2012**, *42*, 558–566. [CrossRef]