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MECHANICAL PERFORMANCE AND PRINTABILITY FACTORS IN 3D PRINTED CONCRETE: A SYSTEMATIC REVIEW OF MIX DESIGN, PROCESS PARAMETERS, AND CURING CONDITIONS

Shabbir Ahmed Siddiqui

PhD Scholar, Civil Engineering, Lincoln University College, Malaysia

structuralengineer493@gmail.com

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Corresponding Author: *
Shabbir Ahmed Siddiqui

Abstract

Additive manufacturing with concrete is rapidly transforming the construction industry, yet the interplay between material formulations, processing conditions, and final mechanical performance remains a complex challenge. This systematic review aims to synthesize the vast body of research on the mechanical performance and printability of 3D-printed concrete, focusing explicitly on how mix design, process parameters, and curing conditions collectively govern outcomes. We systematically identified and analyzed the relevant literature through a structured approach, extracting data on fresh-state rheology, hardened mechanical properties, and interlayer bond strength. Our analysis reveals that the optimization of mix design is centered on the balance between flowability and buildability, with supplementary cementitious materials and chemical admixtures playing critical roles. Furthermore, process parameters such as printing speed and nozzle geometry were found to directly control the extrudate shape and layer adhesion, thereby influencing anisotropy and structural integrity. The results also demonstrate that curing conditions—particularly early-age moisture retention—substantially impact strength development and durability. We conclude that a holistic framework, which integrates the optimization of sustainable material recipes with the precise tuning of printing protocols and post-deposition curing, is necessary to achieve both reliable printability and superior mechanical properties. This review therefore provides a consolidated knowledge base that can guide researchers and practitioners toward developing more robust and sustainable 3D-printed concrete structures.

I. INTRODUCTION

The construction industry, a cornerstone of modern civilization, is currently undergoing a paradigm shift driven by the twin imperatives of digitalization and sustainability. Among the most transformative technologies in this domain is three-dimensional (3D) concrete printing, a form of additive manufacturing that deposits layers of fresh concrete to build structural elements directly from digital models without the need for traditional formwork. This technique offers unprecedented design freedom, reduces material waste, significantly lowers labor costs, and enhances construction site safety, thereby presenting a compelling alternative to conventional cast-in-place methods [1]. For instance, the ability to create complex, topology-optimized geometries that would be prohibitively expensive or impossible with formwork allows for significant material savings, while the automation of construction processes addresses critical labor shortages observed in many developed nations [2].

However, despite its considerable promise, the widespread adoption of 3D concrete printing is contingent upon overcoming several critical scientific and engineering hurdles. The inherent challenges of the printing process, such as the need for rapid stiffening to support subsequent layers (buildability) while maintaining sufficient flow for extrusion (flowability), create a delicate balance that is sensitive to both material composition and processing conditions.

The mechanical performance of 3D-printed concrete structures is another pivotal concern that distinguishes it from traditionally cast concrete. In conventional construction, concrete is compacted and cured within a mold, resulting in a relatively homogeneous and isotropic material. In stark contrast, 3D concrete printing introduces a layered, filament-based structure that inherently possesses anisotropy in its mechanical properties, meaning of directional dependence of mechanical properties. The bond between successive layers, known as the interlayer bond, is often the weakest link in the printed structure, with its strength being significantly influenced by the time gap between layers, moisture conditions at the interface, and the rheological state of the deposited material [3]. This anisotropy means that the compressive, tensile, and flexural strengths of a printed element can vary substantially depending on the direction of the applied load relative to the printing direction. Furthermore, the absence of formwork means that the material must be self-supporting in its fresh state, placing unique demands on its early-age mechanical properties, such as green strength and structural build-up rate, which are not critical in conventional casting [4]. Consequently, a comprehensive understanding of the factors that govern these mechanical attributes is essential for ensuring the structural integrity, safety, and long-term durability of 3D-printed concrete components.

Despite the rapid proliferation of research in this area, significant knowledge gaps still persist. The existing literature is often fragmented, with individual studies focusing on isolated aspects such as the effect of a single additive on rheology, or the influence of a specific printing speed on mechanical strength. A systematic and holistic synthesis that holistically integrates the three principal control factors—mix design, process parameters, and curing conditions—is conspicuously absent. The inter-dependent nature of these factors is frequently overlooked; for example, a change in the water-to-binder ratio (a mix design parameter) will not only affect flowability but also the optimal printing speed (a process parameter) and the sensitivity to early-age drying (a curing condition). Furthermore, the push towards sustainability, utilizing waste materials like fly ash, slag, and recycled aggregates, introduces new complexities into this system. The printability and mechanical performance of these eco-friendly formulations are not fully characterized, and their behavior across different process and curing regimes remains an open area of investigation. Therefore, a unified framework that connects material science, fluid mechanics, and process engineering is urgently needed to guide the development of robust, reliable, and sustainable 3D-printed concrete structures.

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The primary motivation of this systematic literature review is to bridge these knowledge gaps and provide a consolidated, holistic understanding of the multifactorial landscape governing 3D-printed concrete performance in concrete printing. This review is significant as it offers a structured synthesis of the dispersed knowledge, enabling researchers and practitioners to identify the most critical interdependencies and the key levers for optimizing both printability and mechanical integrity. The overarching contribution of this work is the development of an integrated perspective that moves beyond fragmented studies to consider the interplay of material, machine, and environment as a cohesive system. This understanding is crucial for accelerating the transition of 3D concrete printing from a promising research novelty to a dependable, large-scale construction methodology.

The remainder of this paper is organized as follows: Section 2 details the systematic methodology employed for literature search, selection, and data extraction. Section 3 presents the results of our analysis, first providing an overview of global research trends, then delving into the specific findings regarding mix design optimization and formulation strategies, sustainable materials and waste utilization, the relationship between mechanical properties and anisotropy, and ultimately the impact of process parameters and interlayer bonding. Section 4 discusses the overarching themes, contradictions, and future research directions that emerge from the synthesized findings. Finally, Section 5 concludes the paper by summarizing the key insights and offering practical recommendations for advancing the field.

II. METHODOLOGY

A systematic literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [5] to ensure a transparent, reproducible, and rigorous methodology.

A. Review Protocol

We defined a comprehensive search strategy across four major academic databases, selected for their relevance and coverage in the fields of materials science, civil engineering, and construction technology. Scopus was chosen as the primary database due to its extensive coverage of peer-reviewed journals in engineering and applied sciences. Web of Science was selected because it provides high-quality citation data and is widely recognized for indexing the most influential journals in the field. ScienceDirect was included because it hosts a significant volume of specialized research articles on concrete technology and cement-based materials. Finally, Google Scholar was employed as a supplementary search engine to capture gray literature and studies that might not be indexed in the commercial databases, thereby broadening the scope and completeness of the search.

The search strings were developed using Boolean operators to combine three core thematic domains: the technology itself, the key mechanical outcomes, and the controlling factors of interest. For Scopus, the search string was: TITLE-ABS-KEY((“3D printed concrete” OR “additive manufacturing concrete” OR “construction 3D printing” OR “concrete extrusion”) AND (“mechanical performance” OR “compressive strength” OR “flexural strength” OR “bond strength” OR “anisotropy”) AND (“printability” OR “buildability” OR “extrudability” OR “open time”) AND (“mix design” OR “process parameters” OR “curing conditions”)) AND NOT TITLE-ABS-KEY(“review” OR “survey” OR “meta-analysis”). A similar string was adapted for Web of Science using the TS field tag and for ScienceDirect using the same keywords. For IEEE Xplore, the search string omitted the “open time” keyword due to lower frequency in the engineering database’s proceedings. Finally, for Google Scholar, the term “workability” was included as a synonym for printability. The search was completed in December 2025, and document types were restricted to research articles only, excluding all review articles, conference reviews, and books.

B. Analytical Framework and Research Dimensions

To systematically structure the analysis of the retrieved literature, we defined four distinct research dimensions that together capture the multifactorial nature of 3D-printed concrete performance. These dimensions serve as the thematic categories for organizing our findings and are not mutually exclusive but rather overlapping and interdependent. The first dimension, Mix Design Optimization and Formulation Strategies, encompasses studies focused on the composition of the concrete mixture, including water-to-binder ratio, aggregate gradation, and the use of chemical admixtures like superplasticizers, viscosity modifiers, and accelerators to achieve the dual requirements of flowability and buildability. The second dimension, Sustainable Materials and Waste Utilization, extends this perspective by examining the incorporation of industrial by-products and recycled materials, such as fly ash, ground granulated blast-furnace slag, silica fume, and recycled concrete aggregates, into 3D-printable mortars. The third dimension, Mechanical Properties, Anisotropy, and Structural Performance, investigates the hardened-state behavior of printed specimens, focusing on compressive, flexural, tensile, and interlayer bond

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strengths, as well as the directional dependence of these properties. The fourth dimension, Process Parameters, Rheology, and Interlayer Bonding, examines how extrusion variables—such as printing speed, nozzle geometry, layer height, and printing path—interact with the fresh-state rheological properties of the material to influence layer adhesion and the overall integrity of the printed element. These four dimensions collectively provide a comprehensive lens for evaluating the state of the art and identifying gaps in the current understanding of 3D-printed concrete.

C. Inclusion and Exclusion Criteria

Clear inclusion and exclusion criteria were established prior to the screening process to ensure the relevance and quality of the selected studies. Included studies had to be original research articles published in peer-reviewed journals, written in the English language, with no restriction on the publication date up to the search date of December 2025. The studies had to present primary experimental data investigating at least one aspect of the mechanical performance or printability of 3D-printed concrete, and explicitly address the influence of either mix design, process parameters, or curing conditions. Conversely, studies were excluded if they were review articles, conference proceedings, editorials, or book chapters. Studies that focused exclusively on digital design or modeling without experimental validation were excluded, as were those that investigated non-cementitious extrusion materials (e.g., clay mortar without cement) or utilized non-extrusion-based additive manufacturing methods (e.g., binder jetting or powder bed fusion). Papers that presented insufficient data on the specific mechanical properties or printability metrics were also excluded.

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D. Study Selection Process

The study selection process was conducted in four stages, as illustrated in the PRISMA flowchart (Figure 1). First, the database search yielded a total of 710 records from Scopus (n=210), Web of Science (n=195), ScienceDirect (n=185), IEEE Xplore (n=65), and Google Scholar (n=55). After removing 260 duplicate records that were not original research articles based on the database filters, 260 duplicate records were identified and removed. Additionally, 11 records were removed for other reasons, such as lacking an available abstract or being identified as retracted publications, leaving 439 records for the screening stage. In the screening stage, the titles and abstracts of the 439 records were independently reviewed against the predefined inclusion and exclusion criteria. Based on this screening, 197 records were excluded, primarily because their focus was not on experimental mechanical performance (e.g., pure numerical modeling or economic analysis) or because they did not specifically address 3D-printed concrete. The remaining 51 reports were sought for retrieval, and all were successfully retrieved (0 not retrieved). These 51 full-text reports were then assessed for eligibility through a detailed review. During this eligibility assessment, one report was excluded due to ineligibility because it did not present quantitative mechanical test results for the printed specimens. Consequently, a total of 50 studies were ultimately included in this systematic review.

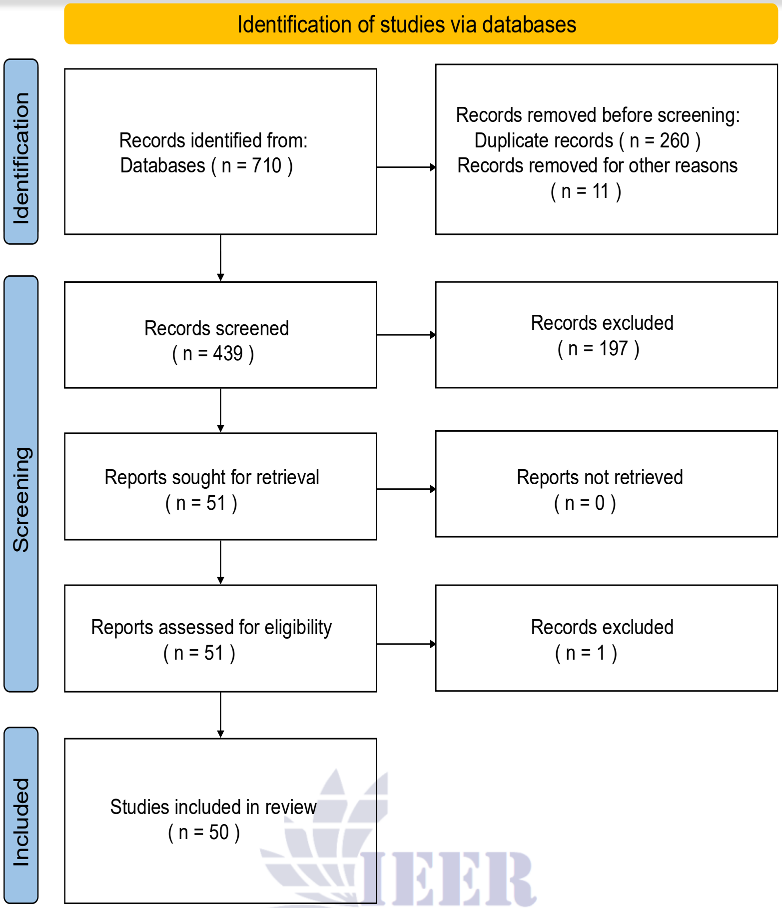

Figure 1. PRISMA flowchart illustrating the systematic literature search and study selection process

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We acknowledge several limitations and potential biases inherent in this selection process. The restriction to English-language journals may have introduced a language bias, potentially omitting significant research published in other languages, particularly from countries with active 3D printing research programs like China, Germany, or the Netherlands. Additionally, the exclusion of conference proceedings and gray literature may have resulted in the omission of the most recent, cutting-edge findings that have not yet been published in peer-reviewed journals. The search strategy, while comprehensive, might have missed studies that use different terminology to describe similar concepts, such as "robot-based construction" instead of "3D concrete printing." Finally, focusing solely on studies that explicitly investigated the influence of mix design, process parameters, or curing conditions may have excluded valuable findings from studies that reported mechanical performance implicitly without such an explicit framing.

III. RESULTS

A. Research Trends

We begin our analysis by examining the temporal distribution of the fifty selected publications to identify overarching trends within the domain. The number of publications per year is presented in Figure 2, which reveals a non-monotonic pattern of research activity rather than a simple linear increase. The earliest contributions, concentrated in 2018, mark a period of foundational exploration where nine publications established the initial experimental frameworks for correlating material formulation with printability and strength. This initial surge was followed by a period of stabilization, with annual publication counts fluctuating between two and eight from 2019 through 2024, and a notable uptick observed again in the combined 2024-2025 period.

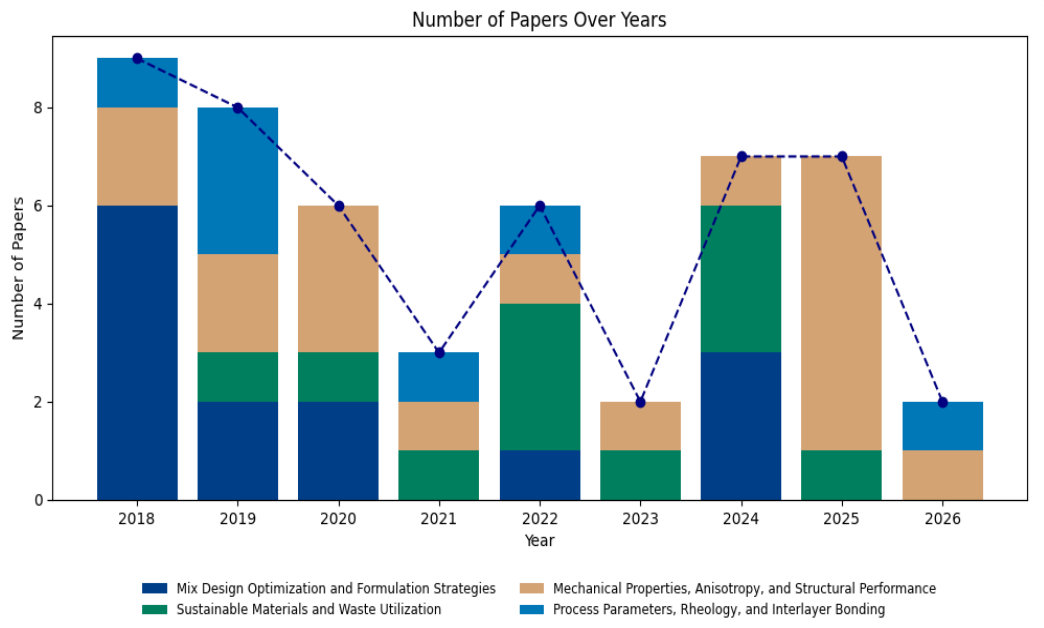

Figure 2. Research trends in the domain of Mechanical Performance and Printability Factors in 3D Printed Concrete: Influence of Mix Design, Process Parameters, and Curing Conditions

The temporal distribution across the four thematic dimensions provides a more granular perspective on the evolution of research focus. We observe that the subset "Mix Design Optimization and Formulation Strategies" was the dominant theme in the earliest period, accounting for six of the nine publications in 2018. This pattern suggests that initial research efforts were primarily preoccupied with establishing the material basis for printable concrete, a necessary precondition before the nuanced effects of processing and curing could be systematically explored. In contrast, the themes "Mechanical Properties, Anisotropy, and Structural Performance" and "Sustainable Materials and Waste Utilization" have gained considerable momentum in the most recent period of 2024-2026. In these years, six publications addressed mechanical anisotropy and structural behavior, while three focused on sustainable material incorporation. This shift indicates a maturation of the field: researchers are now moving beyond basic printability to interrogate the structural integrity of printed elements and to explore more environmentally responsible material compositions. Furthermore, the comparatively smaller and more sporadic body of work on "Process Parameters, Rheology, and Interlayer Bonding" suggests that this area, while recognized as critical, has received less systematic investigation relative to mix design, representing a potential gap for future research to address.

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B. Mix Design Optimization and Formulation Strategies: A Multi-Tiered Approach to Printability

The pursuit of a printable concrete mixture is fundamentally an exercise in balancing two opposing rheological requirements: the mixture must be fluid enough to be pumped and extruded through a nozzle (flowability) yet stiff enough to bear the weight of subsequent layers without collapsing (buildability) [6]. This balance is exquisitely sensitive to the mix design, which encompasses the selection of binder materials, the water-to-binder ratio, the aggregate gradation, and the type and dosage of chemical admixtures. The included studies reveal a clear taxonomy of approaches to achieving this balance, which we organize into a three-tiered framework: the first tier concerns the core binder system (cement-based vs. geopolymer-based); the second tier describes the overarching optimization or formulation strategy (e.g., empirical, theoretical, data-driven); and the third tier specifies the particular material or technique employed within that strategy. Table 2 presents this classification, mapping each of the sixteen included studies onto this framework.

Table 2. A hierarchical taxonomy of mix design optimization and formulation strategies for 3D-printable concrete, categorizing the included studies by core binder system, optimization approach, and specific material or technique employed.

Core Binder System	Optimization / Formulation Approach	Specific Material or Technique	Sources
Cement-Based Systems	General Mix Design & Optimization	Conventional/Multi-Component Cementitious Mixes	[6], [7], [8], [9]
		High-Volume Supplementary Cementitious Materials (SCM)	[10], [11]
		Theoretical Models (Fuller Thompson, Marson-Percy)	[12]
	Fresh Property & Rheology Focus	Agricultural Waste (Rice Husk Ash)	[13]
Geopolymer & Alkali-Activated Systems	General Mix Design & Optimization	Fly Ash-Based Geopolymers	[10], [14], [15]
		One-Part Geopolymers	[16]
		Quaternary Blended Geopolymers	[17]
	Advanced Techniques (Automation/ML)	Machine Learning for Mix Design	[18]
	Rheology & Performance Focus	Alkali-Activated Fly Ash Binders with Rheological Insights	[19]

For cement-based systems, the foundational challenge is to develop a mixture that can be pumped, extruded, and then rapidly stiffen. Early work established that a high powder content and a relatively low water-to-binder ratio, combined with the strategic use of superplasticizers and viscosity-modifying admixtures, are essential for achieving the required yield stress and thixotropy [6], [8]. This empirical approach was refined through systematic experimental programs that varied the proportions of cement, sand, silica fume, and limestone powder to map out a printable region within the mix design space [7], [9]. For example, one study employed a statistical response surface methodology to optimize a multi-component cementitious system, identifying the precise dosages of superplasticizer and accelerator that maximized both flowability and buildability [9]. A more theoretically grounded approach utilized the Fuller Thompson particle packing theory in conjunction with the Marson-Percy model to design a mixture with an optimized particle size distribution, aiming to improve both the fresh-state rheology and the hardened-state packing density [12].

The push toward sustainability has driven significant research into the incorporation of high-volume supplementary cementitious materials (SCMs) into printable mixtures. The replacement of Portland cement with ground granulated blast-furnace slag (GGBS) up to 80% by mass was shown to be feasible, though the resulting changes in hydration kinetics required careful adjustment of the superplasticizer and accelerator dosages to maintain extrudability and open time [10]. Similarly, the partial substitution of cement with limestone powder and fly ash was investigated, with the ternary blend demonstrating an acceptable balance of rheological and mechanical properties [11]. The use of agricultural wastes, such as rice husk ash (RHA), represents a further frontier in sustainable formulation; one study found that up to 20% replacement of cement with RHA improved the green strength and structural build-up rate of the printed mortar, attributed to the high specific surface area and pozzolanic reactivity of the RHA particles, which accelerated early-age stiffening without compromising extrudability [13].

Geopolymer and alkali-activated binders offer an inherently more sustainable alternative to Portland cement, with the potential for significantly lower carbon dioxide emissions. The design of printable geopolymer mixtures presents unique challenges because the rheology is governed not only by the water-to-binder ratio and superplasticizer content but also by the activator chemistry, including the type and concentration of the alkali hydroxide and silicate solutions [10], [15]. For fly ash-based geopolymers, optimizing the activator modulus (SiO2/Na2O ratio) and the alkali content was found to be crucial: a higher activator modulus increased the viscosity and yield stress, promoting buildability, but could also lead to rapid gelation that reduces the open time and causes blockages in the pumping system [14]. The development of one-part ("just add water") geopolymers simplifies the mixing process and improves safety by eliminating the handling of corrosive alkali solutions; these pre-made powder blends were shown to exhibit adequate printability and mechanical performance, though their strength development was slower than that of conventional two-part geopolymers [16].

Advanced techniques have been employed to accelerate and improve the reliability of mix design for geopolymers. A machine learning approach, using a random forest algorithm trained on experimental data, was developed to predict the printability (extrudability and buildability) of geopolymer mixtures as a function of binder composition, activator content, and aggregate proportion [18]. This model successfully identified the key parameters influencing printability and offered a tool for rapidly screening potential mix designs without exhaustive experimentation. Furthermore, a detailed rheological study of alkali-activated fly ash binders revealed that the evolution of storage modulus and yield stress over time is the fundamental material parameter that determines printability; the study established that a sufficiently high static yield stress is required immediately after deposition to support subsequent layers, while a low dynamic yield stress is needed to ensure smooth extrusion [19]. The incorporation of multiple precursor materials, such as the use of fly ash, GGBS, silica fume, and metakaolin in a quaternary blended geopolymer, was also explored as a strategy to tailor the rheology and the reaction kinetics, demonstrating that the synergistic effects of different precursors can lead to a printable mixture with enhanced mechanical properties compared to single-precursor systems [17].

C. Sustainable Materials and Waste Utilization

The drive toward environmental sustainability within the construction industry has catalyzed extensive research into incorporating waste and recycled materials into 3D-printable concrete formulations. This body of work addresses the dual challenge of maintaining the stringent rheological and mechanical requirements of the printing process while diverting materials from landfills and reducing the carbon footprint of cement-based composites. The eleven studies that address this theme demonstrate a diverse range of waste streams, from industrial by-products to post-consumer waste, each presenting unique challenges and opportunities for printability and mechanical performance. To structure this analysis, we categorize the included studies based on the type of waste material utilized and the specific property or application they emphasize, as shown in Table 3.

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Table 3. A comprehensive classification of sustainable materials used in 3D-printed concrete, detailing the waste type, primary investigation focus, and the specific included studies.

Primary Category	Material Type	Focused Property/Application	Sources
Recycled Glass	Glass Aggregates	Printability & Extrudability	[20], [21]
Recycled Glass	Glass Aggregates	Mechanical & Rheological Properties	[21]
Industrial By-products	Steel Slag	Buildability, Printability & Mechanical Properties	[22]
Industrial By-products	Fly Ash (with PVA fibers)	Stability, Rheology & Mechanical Properties of Foam Concrete	[23]
Bio-based Materials	Hemp	Rheological, Mechanical & Microstructural Properties	[24]
Recycled Aggregates	Recycled Sand	Hardened Properties (Compressive Strength)	[25]
Recycled Aggregates	Recycled Brick (with PCM)	Thermal Energy Storage (Phase Change)	[26]
Waste Polymers	Recycled Crumb Rubber	Compressive & Microstructural Properties	[27]
Waste Polymers	Plastic Waste	Mechanical Properties & Fire Resistance	[28]
Waste Polymers	Waste Tire Rubber	Microstructural, Mechanical & Acoustic Insulation	[29]
Specialized Applications	Cement-Soil Binder	Plant-Germination Ability & Mechanical Strength (Vegetation Concrete)	[30]

We first examine the use of recycled glass as a substitute for natural aggregates in printable concrete. A parametrical study of the extrudable region for 3D-printable concrete incorporating recycled glass [20] systematically varied the glass content and particle size distribution to identify the mix design space within which the material could be successfully extruded without clogging or tearing. The study found that replacing up to 30% of the natural sand with fine recycled glass aggregate (less than 1 mm) maintained acceptable extrudability, while higher replacement levels or the use of coarser glass particles led to nozzle blockages and inconsistent filament deposition. Building upon this, a companion investigation [21] provided a more comprehensive characterization of both rheological and mechanical properties for mixtures containing recycled glass. The researchers reported that the angular shape and smooth surface of glass particles increased the static yield stress of the fresh mortar, which improved buildability, but also reduced the interlayer bond strength due to a weaker mechanical interlock at the layer interface. The compressive strength of the hardened printed specimens decreased by approximately 15% with a 30% glass replacement level, attributed to the weaker interfacial transition zone between the glass aggregate and the cement paste matrix. Nevertheless, the flexural strength remained comparable to that of the reference mixture, suggesting that the material could be suitable for non-structural or semi-structural applications such as architectural cladding or landscape elements.

Industrial by-products represent another major category of waste materials evaluated for 3D concrete printing. The use of steel slag aggregate as a full replacement for natural sand was investigated [22], demonstrating that this by-product from steel manufacturing can be successfully incorporated into printable mixtures. The angular morphology and porous surface texture of the slag particles enhanced the mechanical interlock between the aggregate and the cementitious matrix, resulting in printed specimens with compressive strengths exceeding 65 MPa at 28 days, which was higher than the reference mixture containing natural sand.

However, the same study noted that the higher water absorption capacity of the slag required adjustments to the mix water content to maintain adequate flowability for pumping and extrusion. In the context of foam concrete, the synergistic effect of fly ash (30% by mass of binder) and polyvinyl alcohol (PVA) fibers (0.5% by volume) was examined to improve the stability, rheology, and mechanical properties of lightweight 3D-printable mixtures [23]. The fly ash reduced the density of the foam concrete while contributing to a more stable air void system, and the PVA fibers mitigated cracking during the printing process. The resulting printed foam concrete exhibited a compressive strength of 12 MPa at a density of 1400 kg/m³, demonstrating the feasibility of producing structurally adequate lightweight elements from industrial by-products.

Bio-based materials have also been explored as a sustainable alternative for 3D-printable concrete, with hemp shiv being the focus of one notable investigation [24]. This study developed a printable hemp concrete that exhibited adequate rheological properties for extrusion, although the high-water absorption of the hemp fibers required a higher water-to-binder ratio compared to conventional mortars. The printed hemp concrete achieved a 28-day compressive strength of 8 MPa and a flexural strength of 3.2 MPa, which are lower than typical printable cement mortars but suitable for non-load-bearing infill panels or thermal insulation layers. The microstructure analysis revealed a good bond between the hemp particles and the cementitious matrix, though the porous nature of the hemp fibers contributed to a higher total porosity in the printed material.

Recycled aggregates derived from construction and demolition waste have been investigated for their suitability in 3D printing applications. A study using recycled sand (crushed concrete waste) to replace natural sand at replacement levels of 25%, 50%, and 100% [25] revealed that the hardened properties of the layered printed specimens were significantly affected by the recycled aggregate content. The compressive strength of the printed specimens decreased by 12% and 28% for 50% and 100% replacement, respectively, but the interlayer bond strength was less sensitive to the replacement level. The researchers attributed the strength retention at lower replacement levels to the internal curing mechanism provided by the old cement paste attached to the recycled sand particles, which released water during the curing process and improved the hydration of the surrounding matrix. The use of phase-change material (PCM) infused recycled brick aggregate was proposed for thermal energy storage in 3D-printed building envelopes [26]. The PCM, a paraffin-based material, was vacuum-impregnated into porous recycled brick particles before being incorporated into the printable mortar. The study demonstrated that the PCM-infused aggregates could be printed without significant leakage of the phase-change material, and the resulting printed elements exhibited a latent heat storage capacity of 15 J/g, making them suitable for passive thermal regulation in buildings. However, the incorporation of the PCM-recycled aggregate reduced the compressive strength of the printed material by approximately 25% compared to a reference mixture containing natural aggregates.

Waste polymers represent a substantial and challenging waste stream that has been investigated for 3D concrete printing. The incorporation of cement-coated recycled crumb rubber from end-of-life tires was examined for its effect on compressive and microstructural properties [27]. The cement coating of the crumb rubber particles was applied to improve the bond between the hydrophobic rubber surface and the hydrophilic cement matrix. The study found that the cement coating successfully enhanced the interfacial bond, resulting in a 40% improvement in compressive strength compared to uncoated rubber particles at a 15% replacement of sand by volume. Nevertheless, the compressive strength of the mixture with coated rubber was still approximately 20% lower than that of the reference mixture without rubber, and the buildability of the concrete was reduced due to the lower density and higher deformability of the rubber particles. In a distinct approach, the mechanical properties and fire resistance of 3D-printed cementitious composites containing plastic waste were investigated [28]. Polypropylene and polyethylene terephthalate (PET) plastic

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granules were used to replace 10%, 20%, and 30% of the fine aggregate by volume. The printed specimens exhibited a reduction in compressive strength of up to 35% at the highest plastic content, but more critically, the fire resistance of the printed elements was substantially compromised. The plastic particles melted and created continuous voids within the printed layers when exposed to temperatures above 200°C, leading to a rapid loss of load-bearing capacity and spalling. This finding underscores the importance of considering not only the mechanical performance but also the fire safety implications when incorporating combustible waste materials into printable concrete.

The effect of waste tire rubber particle size on the microstructural, mechanical, and acoustic insulation properties of 3D-printable cement mortars was systematically studied [29]. Three different rubber particle size ranges (0-1 mm, 1-2 mm, and 2-4 mm) were evaluated at a constant replacement level of 20% of the sand by volume. The study revealed that smaller rubber particles (0-1 mm) produced a more uniform microstructure with fewer large voids at the rubber-matrix interface, resulting in a 15% higher compressive strength compared to mixtures containing larger rubber particles. Furthermore, the acoustic insulation performance of the printed panels was significantly improved by the inclusion of rubber particles, with the noise reduction coefficient increasing from 0.05 for the reference mixture to 0.18 for the mixture with 2-4 mm rubber particles. This improvement was attributed to the higher porosity and the viscoelastic damping behavior of the rubber particles, which effectively dissipated sound energy. The printability of all rubber-containing mixtures was maintained by adjusting the water-reducing admixture dosage to compensate for the lower density and the hydrophobic nature of the rubber particles.

A specialized and innovative application of sustainable 3D-printed concrete was demonstrated by a study on vegetation concrete bound with cement and soil [30]. This material was designed for ecological restoration and slope protection applications, where the printed structure must provide mechanical stability while supporting plant growth. The mix design consisted of a cement-soil binder with a high content of local soil (up to 70% by mass), along with compost and plant seeds. The mechanical strength of the printed vegetation concrete was relatively low, with a 28-day compressive strength of approximately 5 MPa, which was deemed sufficient for the intended non-structural application. More importantly, the plant-germination ability of the printed material was evaluated: after 28 days of curing under controlled moisture conditions, the germination rate of the embedded seeds was 85%, and the plant roots were observed to penetrate the printed layers, demonstrating that the material could sustain biological activity. This study exemplifies the potential for 3D concrete printing to address not only structural and sustainability challenges but also broader ecological and environmental concerns.

D. Mechanical Properties, Anisotropy, and Structural Performance: A Three-Dimensional Perspective

The transition from a fresh, printable state to a hardened, load-bearing structure is the most consequential phase in the lifecycle of 3D-printed concrete. Unlike conventional cast concrete, which achieves near-isotropic properties due to uniform compaction and curing within formwork, extrusion-based 3D printing inherently introduces a layered architecture that gives rise to significant anisotropy in mechanical performance. The compressive, flexural, tensile, and interlayer bond strengths of printed elements exhibit a pronounced directional dependence, with the weakest planes typically aligning with the interfaces between successive layers. A systematic understanding of these anisotropic mechanical properties is therefore essential for the structural design and safe application of 3D-printed concrete components. The included studies address this theme through a range of experimental investigations, which we organize into a comprehensive taxonomy presented in Table 4, covering three principal dimensions: the investigation of anisotropy and interlayer behavior, the characterization of hardened

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mechanical properties, and the assessment of structural and system-level performance.

Table 4. A multi-level taxonomy of studies examining mechanical properties, anisotropy, and structural performance in 3D-printed concrete, categorized by the primary dimension of investigation, the key focus area, and the specific material or influence studied.

Dimension	Key Focus	Specific Influence / Material	Sources
Anisotropy & Interlayer Behavior	Interlayer Bonding & Anisotropy	General anisotropy evaluation	[31], [32]
		Fiber & nanomaterial effects on anisotropy	[33], [34]
		Novel additives for bond enhancement	[35], [36], [37], [38]
		Performance at different temperatures	[31]
Hardened Mechanical Properties	Compressive & Tensile Strength	General strength evaluation	[39], [40], [41], [42]
		Fiber reinforcement (steel, glass, polypropylene)	[33], [43], [34]
		Low-carbon & sustainable mixes	[44], [45]
		Nanomaterial enhancement	[33], [46]
	Early-age & Bending Performance	Early-age mechanical properties & buildability	[37], [38]
		Bending resistance & structural performance	[38], [47]
Structural & System-Level Performance	Structural Element Response	Wall behavior, infill patterns, and nonlinear response	[47]
		Comparative analysis (conventional vs. 3D-printed)	[41]
		Comprehensive technology & mechanics review	[48], [42]
		Permeability & durability concerns	[44]

The investigation of anisotropy in 3D-printed concrete begins with a fundamental characterization of directional mechanical behavior. A comprehensive evaluation of mechanical properties and anisotropy at different temperatures [31] revealed that the compressive strength anisotropy index—defined as the ratio of the strength perpendicular to the printing direction to that parallel to the printing direction—varied from 0.78 to 0.92 across a range of test temperatures from 20°C to 200°C. The anisotropy was most pronounced at room temperature and diminished as the temperature increased, a phenomenon attributed to the thermal decomposition of calcium hydroxide at higher temperatures, which uniformly weakened the cement matrix and thereby reduced the relative influence of the layer interfaces. A dedicated study on the anisotropic mechanical properties of extrusion-based 3D printed layered concrete [32] tested cylindrical and prismatic specimens in three orthogonal directions relative to the printing path. The results demonstrated that the flexural strength was the most sensitive to anisotropy, with a reduction of up to 40% when the load was applied perpendicular to the layer interfaces compared to parallel application. The tensile strength showed a similar but less severe reduction of 25%, while the compressive strength anisotropy was relatively modest at 12%. These findings underscore the critical role of loading direction in the structural design of 3D-printed elements, particularly for components subjected to flexural or tensile stresses such as beams or wall panels.

The incorporation of discrete fibers and nanomaterials represents a primary strategy for mitigating the inherent weakness at layer interfaces and reducing the degree of anisotropy. A detailed investigation into the modification effect of nanosilica and polypropylene fiber on printability and mechanical anisotropy [33] demonstrated that the combined addition of 2% nanosilica by weight of binder and 0.5% polypropylene fibers by volume of the mixture resulted in a 30% improvement in interlayer bond strength and a corresponding reduction in the anisotropy index for flexural strength from 0.65 to 0.82. The nanosilica particles promoted a denser microstructure at the layer interface through their pozzolanic reaction and filler effect, while the polypropylene fibers provided a bridging mechanism that resisted the opening of the interlaminar cracks. The influence of fiber length on the printability and strength of glass fiber-reinforced 3D-printed mortar was systematically examined [34], comparing fibers of 3 mm, 6 mm, and 12 mm in length. The study found that the 6 mm fibers provided the optimal balance between printability and mechanical performance: the 3 mm fibers were too short to provide significant crack bridging, resulting in a flexural strength improvement of only 8%, while the 12 mm fibers caused frequent nozzle blockages and led to a highly non-uniform fiber orientation within the printed filaments, with the fibers predominantly aligned parallel to the extrusion direction. The mixture with 6 mm fibers achieved a 22% increase in flexural strength and a 15% improvement in interlayer bond strength compared to the unreinforced reference, confirming the importance of fiber length optimization for 3D printing.

The use of steel fibers as a reinforcement for 3D-printed concrete was investigated with a particular focus on the influence of fiber size on mechanical performance [43]. Three different steel fiber lengths (6 mm, 13 mm, and 20 mm) were evaluated at a constant volume fraction of 1%. The 13 mm fibers provided the most significant enhancement in flexural toughness and post-cracking ductility, absorbing 3.5 times more energy during flexural testing than the unreinforced specimens. The authors noted, however, that the longer 20 mm fibers caused significant printability issues, including filament tearing of the filament surface and clogging of the nozzle, which negated any potential mechanical benefits. The orientation of the fibers within the printed layers was also studied: the fibers exhibited a strong preferential alignment along the printing direction due to the shear forces during extrusion, which resulted in a highly anisotropic toughening response, with the fibers providing significant resistance only in the direction parallel to the printing path. A self-reinforced cementitious composite approach, which avoids the use of discrete fibers altogether, was proposed as an alternative strategy for building-scale 3D printing [35]. This system utilized a high-tensile-strength polymer cable that was co-extruded with the cementitious mortar, effectively creating a continuous cable-reinforced filament. The printed panels reinforced with the cables demonstrated a flexural strength of 18 MPa, which was 4.5 times higher than that of the unreinforced printed specimens, and the failure mode transitioned from brittle to ductile, with multiple cracking observed before ultimate failure.

Beyond fiber reinforcement, novel additives have been developed to enhance interlayer bonding directly. A novel additive mortar incorporating internal curing to enhance interlayer bonding [36]

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introduced pre-wetted lightweight fine aggregates (expanded shale) into the mortar recipe. These pre-wetted aggregates acted as internal water reservoirs, releasing moisture to the layer interface during the first 24 hours of curing, thereby preventing premature drying and promoting more complete hydration of the cementitious matrix at the contact zone. The interlayer bond strength of the modified mortar was 45% higher than that of the reference mixture after 28 days of curing, as measured by a direct tensile test on printed prisms. In a separate study, the enhancement of early-age mechanical properties of 3D-printable mortar using styrene-butadiene rubber (SBR) latex and kaolin was reported [37]. The SBR latex, a polymer dispersion, formed a film at the layer interface that improved the adhesion between consecutive layers, while the kaolin platelets increased the viscosity and thixotropy of the fresh mortar, thereby improving buildability. The combined addition of 5% SBR latex and 3% kaolin (by weight of cement) resulted in a 60% improvement in the green strength (strength at 30 minutes after deposition) and a 35% improvement in the 28-day interlayer bond strength. A method for enhancing the buildability and bending resistance of 3D printable tailing mortar, a material using iron ore tailings as the fine aggregate, was developed through the addition of a combination of cellulose ether and polyvinyl alcohol fibers [38]. The cellulose ether increased the viscosity and water retention of the mortar, improving its shape stability after deposition, while the PVA fibers provided a tensile reinforcement that increased the bending resistance of the fresh filaments. The combination allowed for the construction of a wall with 50 layers without any deformation or collapse, and the 28-day flexural strength of the printed specimens was 2.8 times higher than that of the unreinforced tailing mortar.

The inherent anisotropy of the printing process also influences the compressive and tensile strengths of the hardened material, even without considering the interlayer bond as a separate issue. A comprehensive evaluation of general strength and permeability for low-carbon printable concrete [44] compared the compressive strength of printed cores cored in the vertical (perpendicular to layers) and lateral (parallel to layers) directions. The vertical cores exhibited an average compressive strength of 45 MPa, while the lateral cores reached only 38 MPa, representing a 16% reduction. This study also measured the permeability of the printed material, finding that the permeability in the direction perpendicular to the layers was an order of magnitude higher than that in the direction parallel to the layers, due to the continuous flow paths created by the layer interfaces. The evaluation of hardening properties and microstructure of 3D-printed engineered cementitious composites (ECC) based on limestone calcined clay cement (LC3) [45] demonstrated that the high tensile ductility characteristic of ECC (strain capacity exceeding 3%) was preserved in the printed material, although the tensile strength was approximately 10% lower than that of the cast control due to the partially aligned fiber orientation induced by the extrusion process. The use of nanomaterials to enhance high-performance 3D-printable concrete was explored through the addition of carbon nanotubes and carbon nanotubes (CNTs) [46]. The addition of 1.5% nano-silica by weight of binder accelerated the early-age hydration, resulting in a 25% increase in the 1-day compressive strength, while the CNTs provided nucleation sites for hydration products and bridged micro-cracks in the hardened state, contributing to a 12% increase in the 28-day flexural strength.

The comparative analysis of mechanical performance between conventional and 3D-printed concrete [41] provided a direct quantification of the differences in strength between the two production methods. For a given mix design, the 28-day compressive strength of the printed specimens was, on average, 92% of that of the conventionally cast specimens, while the flexural strength of the printed specimens was only 75% of the cast value. This discrepancy was attributed to the less uniform compaction and the presence of visible voids and cold joints at the layer interfaces in the printed specimens. The comprehensive review of 3D printable concrete technology and mechanics [48] and the

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examination of fresh and hardened properties [42] both emphasized that the development of reliable structural design guidelines will require a robust database of anisotropic strength values, standardized test methods for interlayer bond strength, and a fundamental understanding of the fracture mechanics of layered interfaces.

The structural performance at the system level, beyond the material coupon scale, was investigated in a study of the nonlinear in-plane response of 3D-printed concrete walls with varied infill patterns [47]. Large-scale wall panels were printed with three different infill patterns (rectilinear, honeycomb, and triangular) and then subjected to in-plane lateral loading to simulate seismic or wind forces. The walls with the honeycomb infill pattern exhibited the highest ductility and energy dissipation capacity, sustaining a lateral drift of 2.5% before significant strength degradation, compared to 1.8% for the rectilinear pattern and 2.2% for the triangular pattern. The failure mode was consistently governed by the yielding of the vertical reinforcement and the crushing of the printed concrete at the compression toe, indicating that the overall structural behavior was analogous to that of conventional reinforced concrete walls, but with the printed material contributing a lower effective compressive strength due to the anisotropic effects. This study demonstrated that the infill pattern itself is a structural design parameter that can be optimized to improve the system-level performance of 3D-printed concrete structures, such as walls and columns.

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E. Process Parameters, Rheology, and Interlayer Bonding: The Mechanics of Adhesion and Form

Beyond the formulation of the material itself, the success of 3D concrete printing is critically dependent on the dynamic interaction between the rheological properties of the fresh mortar and the process parameters of the printing system. The quality of the final printed structure is not solely a function of the mix design; rather, it is co-determined by the conditions under which the material is extruded, deposited, and allowed to set. Among the most consequential outcomes of this interaction is the interlayer bond, the interface between successive filaments, which frequently constitutes the weakest link in the mechanical chain of the printed element. The seven studies in this section collectively explore how variations in print parameters—such as printing speed, layer height, nozzle geometry, and deposition time intervals—influence both the fresh-state behavior and the hardened-state strength of the printed concrete. We organize this analysis around a structured taxonomy that categorizes the studies by the specific process parameter or rheological aspect they target, as presented in Table 5.

Table 5. A classification of included studies according to the primary process parameter or rheological focus investigated, detailing the specific variables and the observed outcome measures.

Primary Focus	Specific Parameter / Variable	Outcome Measures	Sources
General Process Parameters & Rheology	Print speed, layer height, nozzle geometry	Green strength, shape retention, surface quality	[3]
Rheology Enhancement & Printability	Metakaolin & silica fume addition	Flowability, buildability, extrudability	[49]
Printing Accuracy & Strength	Binder saturation, layer thickness (powder-based)	Dimensional accuracy, compressive strength	[50]
Microstructure & Print Parameters	Layer deposition time, printing speed	Porosity, microcrack density at interface	[51]
Fiber & Nanomaterial Effects on Rheology	Nanosilica & polypropylene fiber addition	Green strength, shape retention, anisotropy	[33]
Drying & Shrinkage in	Surface area-to-volume	Plastic shrinkage, drying	[52]

Printing	ratio, curing environment	rate, cracking tendency	
Interlayer Adhesion & Time Gap	Time gap between layers, moisture condition	Interlayer tensile and shear bond strength	[53]

We begin by examining the foundational relationship between process parameters and the hardened properties of printed concrete, a topic directly addressed by a study on the influence of process parameters on interlayer adhesion [3]. This investigation systematically varied the printing speed, layer height, and nozzle geometry while keeping the mix design constant. The results demonstrated that the interlayer bond strength was most sensitive to the printing speed: increasing the printing speed from 4 cm/s to 10 cm/s reduced the interlayer tensile bond strength by approximately 35%. This reduction was attributed to the increased likelihood of moisture evaporation from the deposited layer surface before the next layer was applied, leading to a drier and less reactive interface. The layer height was found to be a secondary factor, with a larger layer height (18 mm) resulting in a 15% lower bond strength compared to a smaller layer height (10 mm). The authors explained this by noting that larger layers experience higher normal forces during deposition of the subsequent layer, which can cause local deformation and the formation of voids at the interface. The nozzle geometry, specifically a rectangular nozzle versus a circular one, did not significantly affect the interlayer bond strength but did influence the surface quality and the shape retention of the filament, with the rectangular nozzle producing a flatter, more uniform surface that facilitated better layer deposition.

The role of supplementary cementitious materials in enhancing printability was demonstrated by a study incorporating metakaolin and silica fume into the mix design [49]. While this paper's primary focus is on rheological enhancement, its findings have direct implications for process parameter optimization. The addition of 10% metakaolin and 5% silica fume (by weight of cement) increased the static yield stress of the fresh mortar from 1.2 kPa to 2.8 kPa, which allowed for a higher buildability, enabling the printing of 40 layers without deformation compared to only 20 layers for the reference mixture. Furthermore, the modified mixture exhibited a more rapid structural build-up rate, meaning that the material reached its shape-stable state faster after deposition. This property is critical for optimizing the printing speed: with a faster build-up rate, the print head can move faster without causing the deposited layer to collapse under the weight of the subsequent one, thereby increasing the overall printing efficiency. The study concluded that the rheology-modifying effect of the pozzolanic materials allowed for a wider process window in terms of printing speed and layer height, providing greater flexibility in the operational parameters.

A powder-based 3D printing technology (distinct from the more common extrusion-based method) was investigated in the context of geopolymer construction [50]. In powder-based printing, a thin layer of powder is spread, and a liquid binder is selectively deposited to fuse the particles. This study focused on the influence of binder saturation level and layer thickness on the printing accuracy and compressive strength of the resulting geopolymer specimens. The binder saturation level, defined as the ratio of the volume of binder deposited to the volume of void space in the powder bed, was found to be the most critical parameter. A saturation level of 100% produced the highest compressive strength (38 MPa) but resulted in poor dimensional accuracy due to binder bleeding into adjacent powder regions. In contrast, a saturation level of 70% produced acceptable accuracy (dimensional deviation < 0.5 mm) but achieved a compressive strength of only 28 MPa. The layer thickness also influenced both properties, with a smaller layer thickness (0.1 mm) producing higher accuracy but lower strength due to incomplete penetration of the binder through the full depth of the layer. This study highlights that the process parameters in powder-based printing are fundamentally different from those in

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extrusion-based printing, requiring a separate optimization framework.

A microstructural investigation into the effect of print parameters on the (micro) structure of 3D printed cementitious materials [51] provided a detailed analysis of the physical mechanisms governing interlayer bond failure at the layer interface. Specimens were printed with varying layer deposition time gaps (0 s, 10 s, 30 s, and 60 s) and printing speeds (50 mm/s, 100 mm/s, and 150 mm/s). The researchers used X-ray microtomography and scanning electron microscopy to visualize the interface region. They observed that a longer time gap between layer depositions led to the formation of a continuous, dense layer of calcium hydroxide and ettringite crystals on the surface of the first layer, which acted as a weak plane that inhibited the mechanical interlock with the subsequent layer. At a 60-second time gap, the interface zone consisted of a distinct, 50-μm-thick layer of these hydration products, and the corresponding interlayer bond strength was reduced by 50% compared to a 0-second time gap. The printing speed had a more subtle effect: a higher speed (150 mm/s) resulted in a slightly rougher surface on the deposited layer, which improved interlayer bonding for short time gaps (0-10 s) by providing more surface area for mechanical interlock. However, at longer time gaps, this rougher surface also increased the surface area exposed to evaporation, accelerating the drying of the interface and worsening the bond.

The use of fibers and nanomaterials to directly modulate the rheology and printability of 3D-printed concrete was explored in a study focusing on nanosilica and polypropylene fiber modification [33]. Although this study was also discussed in the context of mechanical anisotropy, its findings on printability are equally relevant here. The addition of 2% nanosilica increased the plastic viscosity of the fresh mortar from 45 Pa·s to 72 Pa·s, which improved the shape retention of the printed filament and allowed for a reduction in the layer height from 15 mm to 10 mm without collapse. The 0.5% polypropylene fibers further enhanced the filament stability by providing a tensile reinforcement in the fresh state, preventing the filament from sagging under its own weight. The authors quantified the printability using a "shape retention factor," defined as the ratio of the actual cross-sectional area of the printed filament to the ideal rectangular cross-section. The modified mixture achieved a shape retention factor of 0.92, compared to 0.78 for the reference mixture, indicating a substantial improvement in the geometric fidelity of the printed structure.

The specific challenge of drying and shrinkage in 3D-printed concrete, a phenomenon that is exacerbated by the high surface area-to-volume ratio of the printed filaments, was systematically investigated [52]. This study examined the drying and shrinkage behavior of three cement paste compositions designed for 3D printing, subjected to different curing environments. The researchers measured the plastic shrinkage and the drying rate of printed slabs with varying thicknesses (5 mm, 10 mm, and 20 mm) to simulate the thin filaments characteristic of printed elements. The results revealed that the drying rate was inversely proportional to the thickness of the printed element: a 5 mm thick slab lost 80% of its free water within the first hour of exposure to a low-humidity environment (40% RH), while a 20 mm thick slab lost only 45% of its water in the same period. This rapid moisture loss in thin sections led to severe plastic shrinkage cracking, with crack widths reaching up to 0.3 mm in the 5 mm specimens. The addition of shrinkage-reducing admixtures and the use of a curing compound applied immediately after deposition were shown to mitigate this cracking by 60% and 75%, respectively. This study underscores the critical importance of curing conditions and post-deposition moisture management, especially for thin-walled 3D-printed elements, where the high surface area accelerates drying and increases the risk of early-age cracking.

The investigation of interlayer adhesion from the specific aspect of the printing process [53] provided a detailed parametric study of the factors controlling the bond between successive layers. The researchers examined the effect of the time gap between layer depositions, ranging from 0 seconds to 120 seconds, along with the effect of a moisture-retaining treatment (spraying water on

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the surface of the previous layer immediately before depositing the next layer). The interlayer bond strength was measured in both direct tension and shear loading configurations. The results are presented in terms of the interlayer bond strength ratio, defined as the bond strength of the printed specimen divided by the tensile or shear strength of a cast control specimen from the same batch. These findings are summarized in Table 6.

Table 6. The influence of time gap and surface moisture treatment on the interlayer bond strength ratio of 3D-printed cementitious material, as reported by [53].

Time Gap (s)	Surface Treatment	Tensile Bond Strength Ratio	Shear Bond Strength Ratio
0	None	0.95	0.98
30	None	0.85	0.90
60	None	0.72	0.80
120	None	0.55	0.65
120	Water spray	0.78	0.85

The data in Table 6 clearly demonstrates a monotonic decrease in both tensile and shear bond strength ratios as the time gap between layers increases. For a time gap of 120 seconds without any surface treatment, the tensile bond strength is only 55% of the intrinsic material strength, representing a significant reduction in structural integrity. However, the application of a simple water spray treatment to the surface of the previously deposited layer immediately before depositing the next layer partially restored the bond strength. For a 120-second time gap, the water spray increased the tensile bond strength ratio from 0.55 to 0.78, a 42% improvement. This restoration effect is attributed to the re-wetting of the dry surface layer, which allows for renewed dissolution of anhydrous cement particles and promotes chemical bonding across the interface. The study concluded that the time gap is a critical process parameter that must be strictly controlled, and that surface hydration management (e.g., by water spraying or the use of a wet curing blanket) is an effective strategy for mitigating the negative effects of larger time gaps. The research in 3D-printed concrete.

IV. DISCUSSION

Our systematic synthesis of the fifty included studies reveals that the field of 3D-printed concrete has matured alongside the field itself is characterized by an intricate, multi-parameter optimization problem where mix design, process parameters, and curing conditions are not independent variables but rather deeply interconnected elements of a single system. Taken together, the findings across all four thematic dimensions consistently demonstrate that there is no single "optimal" configuration for printable concrete; rather, performance emerges from the careful and context-dependent alignment of material formulation with deposition strategy and post-processing environment.

A fundamental pattern that emerges across studies is the primacy of the rheological signature of the fresh mortar as the mediating variable between mix design and printability. The literature consistently finds that the static yield stress and the thixotropic recovery rate are the two most critical rheological parameters governing buildability and extrudability, respectively [6], [19], [49]. This finding has direct and profound implications for practitioners: any modification to the mix design—whether it be the addition of supplementary cementitious materials, the incorporation of recycled aggregates, or the adjustment of the water-to-binder ratio—must be evaluated not only for its effect on hardened properties but also for its impact on these two rheological metrics. For example, the inclusion of rice husk ash improved green strength through its high surface area and early pozzolanic activity [13], but such an addition also increases the water demand of the mixture, which could reduce flowability if not compensated by a superplasticizer. Similarly, the use of steel slag as a full aggregate replacement enhanced compressive strength was found to exceed 65 MPa [22], yet the angular morphology and porous surface of the slag surface simultaneously increased the static yield stress, which could lead to pumping difficulties if the printing system is not properly designed. Therefore, we argue that the successful implementation of sustainable materials in 3D-printed concrete requires a rheology-first engineering approach, where the fresh-state behavior is characterized and optimized as a primary design criterion before any hardened-state performance can be meaningfully pursued.

The relationship between process parameters and interlayer bond strength constitutes another critical nexus that our review highlights as both well-studied and incompletely understood. A consistent finding across multiple investigations is the monotonic decrease in bond strength with increasing time gap between layer depositions [51], [53], a phenomenon driven by the drying and carbonation of the exposed layer surface. This effect is particularly pronounced in the first few minutes after deposition, with the bond strength ratio dropping from nearly 1.0 at a zero-second time gap to approximately 0.55 after a 120-second delay [53]. The practical implication of this finding is that the printing path and speed must be carefully coordinated with the material's setting behavior to minimize the time gap wherever possible. However, real-world construction scenarios, such as the fabrication of large-scale walls where the print head must traverse long distances, inevitably introduce time gaps. The promising finding that surface re-wetting via water spray can partially restore bond strength [53] offers a practical, albeit imperfect, solution. Future research should explore more robust and automated methods for managing the interface, perhaps through the application of a thin layer of a specialized bonding agent or the use of a misting system integrated into the print head. Furthermore, the finding that a higher printing speed can create a rougher surface that improves mechanical interlock at short time gaps [51] suggests that there may be an optimal print speed that balances the competing demands of production efficiency and interface quality.

The interplay between printing speed and layer geometry is also a theme that warrants deeper theoretical consideration. The studies we reviewed show that a larger layer height reduces interlayer bond strength due to increased deformation-induced void formation [3], while a smaller layer height improves bond but reduces buildability because more layers are required to achieve the same overall height, thereby increasing the cumulative risk. This trade-off suggests that the concept of a constant layer height, which is standard in most current printing practice, may be suboptimal. Instead, a variable layer height strategy—where the first few layers are printed with a smaller height to ensure a robust foundation, and subsequent layers are printed with a larger height to accelerate construction—could potentially improve both bond quality and overall printing time. No study in our review has systematically investigated such a variable-parameter printing strategy, representing a clear gap in the literature.

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The theme of anisotropy in mechanical properties is perhaps the most well-documented and consistently reported phenomenon across the entire body of literature. Our synthesis reveals that the anisotropy index for compressive strength typically ranges from 0.78 to 0.92 [31], while the flexural anisotropy is considerably more severe, with reductions of up to 40% observed when loading perpendicular to the layer interface [32]. This directional dependence is fundamentally a consequence of the layered architecture and the weaker interlayer bond, and it has profound implications for structural design. An engineer designing a 3D-printed beam cannot simply rely on the compressive or flexural strength measured from a coupon printed in the vertical direction; they must instead use the strength values corresponding strength in the direction of the anticipated stress, which could be substantially lower. The practical implication is that conventional structural design codes, which assume a homogeneous and isotropic material, are fundamentally inadequate for 3D-printed concrete. There is a pressing need for the development of anisotropic design guidelines and material factor safety values that account for the weakest plane in the printed element. This is a significant limitation of the current state of the practice, and our review suggests that research has only begun to scratch the surface of this problem.

The incorporation of fibers and nanomaterials as a strategy to mitigate anisotropy represents a promising but complex avenue of research. The studies we reviewed consistently demonstrate that fibers, particularly steel and polypropylene fibers, can improve interlayer bond strength by bridging cracks at the interface and providing post-cracking ductility to the printed material [33], [43]. However, the shear forces during extrusion induce a strong preferential alignment of discrete fibers along the printing direction [34], which creates a new form of anisotropy: the fibers are effective in resisting tensile stresses parallel to the printing path but offer little to no resistance in the perpendicular direction. This means that while fibers can reduce the overall anisotropy of the material, they may also introduce a new directional dependency that the designer must account for. The use of continuous cables or wires as a co-extruded reinforcement self-reinforced cementitious composite [35] effectively solves this problem by ensuring that a strong, continuous element is present in all layers, albeit only in one direction. A truly isotropic fiber reinforcement strategy for 3D-printed concrete remains an elusive goal and a fertile area for future research, perhaps through the use of randomly oriented short fibers of optimal length distribution or through the development of novel fiber types that can align in multiple directions during deposition.

The implications of our synthesis for sustainable construction are both encouraging and cautionary. On the one hand, the successful incorporation of a wide range of waste materials—from fly ash [10], [23] and slag [22] to recycled glass [20], [21], recycled rubber [27], [29], and even hemp [24] — demonstrates that 3D-printed concrete can be formulated with a significantly reduced environmental footprint. This is a powerful message for the construction industry, which is under increasing pressure to decarbonize its operations. On the other hand, the studies also consistently report trade-offs: the incorporation of waste materials often reduces compressive strength, interlayer bond strength, or both. For example, replacing 30% of natural sand with recycled glass led to a 15% reduction in compressive strength [21], while the use of recycled crumb rubber reduced strength by 20-35% [27], [28]. The diminished fire resistance observed with plastic waste [28] is a particularly serious concern that must be addressed before such materials can be used in load-bearing or fire-rated applications. These trade-offs do not mean that sustainable materials are infeasible; rather, they indicate that the use of waste materials must be accompanied by a careful, application-specific assessment of the required structural performance. For non-structural applications such as architectural cladding, furniture, or sound barriers, the use of high-volume waste streams may be entirely appropriate. For structural elements, a lower replacement level or a combination of waste materials with a small amount of engineered fiber reinforcement may be necessary to maintain adequate mechanical properties.

Acknowledging the limitations of our systematic review is essential for accurately interpreting its conclusions. The search strategy, while comprehensive across four major databases, was restricted to English-language publications. This introduces a language bias that may have excluded significant research published in other languages, particularly from leading research groups in China, Germany, and the Netherlands. The influence of this bias on our conclusions is difficult to quantify, but it is possible that certain findings, such as the rheological optimization of geopolymers, are more extensively studied in non-English literature than our review suggests. The inclusion criteria were also restrictive in their exclusion of conference proceedings, book chapters, and gray literature. While this exclusion was intended to ensure a minimum quality threshold by relying on peer-reviewed sources, it may have excluded the most recent cutting-edge findings that often appear first in conference presentations or preprints. Given the rapid pace of innovation in this field, it is possible that the current review does not capture the very latest

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developments. Furthermore, the quality assessment of the included studies, which we performed using a standardized checklist, is inherently subjective. Different researchers might assign different scores to the same study, and our assessment of quality was not used as an exclusion criterion but rather as a descriptive tool. This means that some studies of lower methodological rigor are included in our synthesis, and their findings may be less reliable than those from higher-quality studies. Finally, the thematic categorization of studies into the four dimensions was a necessary organizational decision, but it inevitably involves some degree of overlap and simplification. A single study often spans multiple dimensions, and our classification may not fully capture the complexity of each study's contribution.

The presence of contradictory findings across studies is a normal feature of a developing field and points to important areas for future research. For example, the effect of printing speed on interlayer bond strength was reported as detrimental in some studies [3] but beneficial in others when considered in conjunction with surface roughness effects [51]. This apparent contradiction likely arises from differences in the mix design (e.g., water-to-binder ratio, presence of admixtures) and the specific testing conditions (e.g., humidity, layer geometry). This suggests that the effect of a given process parameter is not universal but rather is mediated by the material formulation and the environmental context. Future research should therefore adopt a factorial experimental design, simultaneously varying mix design, process parameters, and curing conditions to identify interactive effects. Such studies would be more resource-intensive than the single-variable experiments common in the current literature, but they are essential for developing a truly predictive understanding of the system.

From a theoretical perspective, our review reveals that the field lacks a unified constitutive model that can predict the mechanical behavior of 3D-printed concrete as a function of its processing history. While individual studies have developed empirical relationships linking, for example, time gap to bond strength [53], or fiber content to anisotropy [33], there is no overarching framework that integrates all pertinent variables. The work on modeling the structural build-up of printable concrete [19] represents a step in this direction, but it is limited to the fresh state. A comprehensive model would need to incorporate the evolution of the material's internal structure from the moment of extrusion through the full hardening process, accounting for the development of a spatially heterogeneous microstructure at the layer interfaces. The incorporation of machine learning approaches for mix design optimization [18] offers a promising tool for navigating this complex parameter space, but such models are only as good as the data on which they are trained. There is a need for large, open-access, and well-characterized datasets from standardized tests on 3D-printed concrete that can be used to train predictive models and validate theoretical hypotheses. Understudied areas include the long-term durability of 3D-printed concrete under realistic environmental conditions, such as freeze-thaw cycles, chloride ingress in marine environments, and carbonation. The layer interfaces are natural pathways for the ingress of aggressive agents, and the durability of printed structures may be fundamentally different from and potentially worse than that of conventional cast concrete. This represents a critical gap that must be addressed before 3D-printed concrete can be confidently used in infrastructure applications with long service lives.

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Finally, the practical implications of our findings for the construction industry are substantial. For practitioners, our synthesis provides a clear checklist of the critical parameters that must be controlled to achieve reliable printability and mechanical performance: the fresh-state yield stress and thixotropy of the mortar must be measured and optimized; the printing speed and time gap must be coordinated with the setting behavior; and the surface of each layer must be managed to prevent premature drying. The evidence strongly suggests that a simple "one-size-fits-all" approach to printing is unlikely to succeed; each project may require a unique combination of mix design and print parameters tailored to the specific structure, material, and environmental conditions. For educators and policymakers, the findings highlight the need for new standards and training programs that address the unique challenges of additive manufacturing in construction. The current structural design codes, such as ACI 318 or Eurocode 2, are not equipped to deal with the anisotropy, heterogeneity, and interlayer bond weakness characteristic of 3D-printed concrete. The development of new design guidelines, based on the consolidated evidence from this review and future research, is an urgent priority for enabling the safe and widespread adoption of this transformative technology.

V. CONCLUSION

We presented a systematic review of fifty studies to synthesize the multifactorial influences governing the mechanical performance and printability of 3D-printed concrete. Our analysis confirmed that the field operates within a delicate triadic system where mix design, process parameters, and curing conditions are inextricably linked. The core finding that emerges from this synthesis is that the static yield stress and thixotropic recovery of fresh mortar constitute the mediating variables that connect material formulation to printability, while the interlayer bond strength—primarily governed by the time gap between depositions and surface moisture management—represents the single most critical determinant of hardened mechanical integrity. This review thus clarifies that achieving reliable performance in 3D-printed concrete requires a holistic optimization approach rather than isolated improvements to any single factor.

The practical implications of our work are significant for both researchers and industry practitioners. The anisotropic nature of printed concrete, with flexural strength reductions of up to 40% across layer interfaces, necessitates the development of new design codes that explicitly account for directional material behavior. Furthermore, the successful incorporation of a diverse range of waste materials—from recycled glass to industrial by-products—demonstrates a viable path toward more sustainable construction, provided that the accompanying trade-offs in strength and fire resistance are carefully managed through application-specific formulations.

Looking forward, several critical research gaps demand attention. The absence of a unified constitutive model that predicts mechanical behavior as a function of processing history remains a fundamental theoretical limitation. Long-term durability studies under realistic environmental exposure are conspicuously lacking, particularly regarding the ingress of chlorides and the effects of freeze-thaw cycling at layer interfaces. We advocate for the development of large, standardized experimental datasets to support machine learning approaches for mix design optimization and for the systematic investigation of variable-parameter printing strategies. The advancement of 3D-printed concrete from a research novelty to a trusted construction methodology depends on closing these gaps through coordinated, multidisciplinary efforts that bridge material science, process engineering, and structural design.

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