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Review Article

A Review on the Relationship Between Rheological Properties and 3D Printing Parameters for Optimizing Concrete Printability and Structural Performance

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Abstract

3D concrete printing (3DCP) has emerged as an innovative construction technique that enables the automated fabrication of structures without the need for formwork, offering advantages such as design flexibility, material efficiency, and improved safety. The successful implementation of 3DCP relies heavily on the rheological properties of the printing material, which govern key parameters such as pumpability, extrudability, buildability, and interlayer bonding strength. This review explores how key rheological parameters, including static and dynamic yield stress, plastic viscosity, and structural build-up rate, affect not only the flow and deposition of fresh concrete but also interlayer bonding strength and overall structural integrity. Additionally, this review examines the influence of printing parameters such as layer deposition time, nozzle size, and print speed on interlayer adhesion and the overall stability of the printed structure. By synthesizing experimental and numerical studies, this work provides a comprehensive guideline for evaluating and predicting the performance of 3D printed concrete through rheological testing, facilitating the optimization of material formulations and printing processes for enhanced printability and structural reliability.

Keywords: 3D concrete printing, rheology, printability, interlayer bonding

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Highlights

- Rheological properties such as yield stress and viscosity govern pumpability, extrudability, and buildability in 3DCP.
- Interlayer bonding and structural stability are closely linked to printing parameters like speed and nozzle geometry.
- Analytical models enable prediction of failure mechanisms, supporting optimization of print quality and build height.

1 Introduction

Extrusion-based 3D concrete printing (3DCP) is rapidly emerging as a groundbreaking digital construction method, allowing the automated creation of complex architectural forms without the need for conventional formwork (Buswell et al., 2018; M. Khan & McNally, 2023, 2024). Unlike other additive manufacturing approaches such as powder-bed fusion or binder jetting, extrusion-based 3DCP operates by depositing layers of fresh cementitious material through a nozzle under regulated pressure. The effectiveness of this technique is largely dependent on the rheological characteristics of the concrete in its fresh state, which influence its behaviour during pumping, extrusion, and deposition (Roussel, 2018). Key rheological factors, such as static and dynamic yield stress, plastic viscosity, and thixotropy, play a crucial role in determining the material's flow under pressure, its shape retention post-deposition, and its ability to support additional layers.

Managing these parameters is particularly challenging due to their time-dependent nature, especially as the material transitions from a fluid-like to a more solid-like consistency. Recent studies underscore the need for precise characterization of this evolving behaviour, noting the close interplay between material rheology, process parameters, and the resulting structural performance (Chang et al., 2023; Zhao et al., 2022). In addition, experimental investigations have shown that printing variables, such as nozzle shape, printing speed, standoff height, and the timing between layer placements have a marked impact on the bonding between layers and the overall mechanical performance of printed structures (Zhang & Sanjayan, 2023; Zhou et al., 2022; Zhang et al., 2022).

This review compiles current theoretical frameworks and experimental insights that connect rheological behaviour, process settings, and structural reliability in extrusion-based 3DCP. By presenting a brief view of these interdependent factors, the review aims to guide the development of optimized concrete mixes and refined printing techniques, paving the way for robust, large-scale implementation of additive manufacturing in the construction sector.

2 Rheological Behaviour in 3DCP

Understanding the rheological characteristics of 3D printing concrete is fundamental to the success of the printing process and are primarily defined by key parameters such as static yield stress, dynamic yield stress, plastic viscosity, and thixotropy (Tay et al., 2019; Xu et al., 2022).

Static yield stress refers to the minimum shear stress required to initiate flow in a material at rest. It reflects the degree of internal structuration and flocculation developed during rest periods and is crucial for maintaining the shape and stability of printed layers after deposition. In contrast, dynamic yield stress is the minimum stress needed to maintain flow under continuous shearing, typically lower than the static value due to the partial breakdown of the internal structure. These two parameters govern the transition between solid-like and liquid-like behaviour during printing and largely determine the response of the material in both extrusion and post-deposition stages (Roussel, 2018). Plastic viscosity represents the slope of the stress–strain rate curve once yield has been exceeded and characterizes the internal friction among particles during flow. It controls the resistance of the material to shear-induced motion and directly impacts the pressure required during pumping and extrusion processes (Rahman et al., 2024).

Moreover, fresh concrete can exhibit either shear-thickening or shear-thinning behaviour. Shear-thickening occurs when viscosity increases with rising shear rates, often due to intensified particle collisions and frictional interactions. Conversely, shear-thinning is marked by a decrease in viscosity under increasing shear rates, which results from particle alignment and breakdown of inter-particle networks, facilitating smoother flow (Tay et al., 2019). Thixotropy is another critical time-dependent rheological parameter, describing the reversible structural build-up of the material when at rest and its breakdown under shear (Mohan et al., 2021). It arises from colloidal interactions and early hydration processes and governs the rate at which yield stress recovers between layers. High thixotropy is beneficial for buildability, as it enhances shape retention, but excessive thixotropic recovery may hinder extrusion continuity (Roussel, 2006).

Precisely evaluating the shear conditions throughout various stages of the printing process is essential to avoid nozzle blockages, maintain steady and consistent extrusion, and preserve the structural integrity between printed layers. To quantitatively characterize the stress–deformation behaviour of materials under shear, commonly used rheological models include the Bingham model, the modified Bingham model, and the Herschel–Bulkley model (Jiao et al., 2017; Peng & Unluer, 2023).

3 Printability

Printability is a general term that includes the critical fresh-state properties required for successful execution of extrusion-based 3DCP. As illustrated in Fig. 1, a typical 3DCP system comprises a material mixing and delivery unit, an extrusion apparatus (such as screw or piston extruders), and a computer-controlled robotic arm or gantry system for material deposition (Lee et al., 2024). To ensure printability throughout the printing process, the cementitious mixture must transition seamlessly through three sequential performance stages: pumpability, extrudability, and buildability. Each of these stages imposes distinct but interconnected requirements on the material's rheological behaviour (Arunothayan et al., 2023; Zhao et al., 2022).

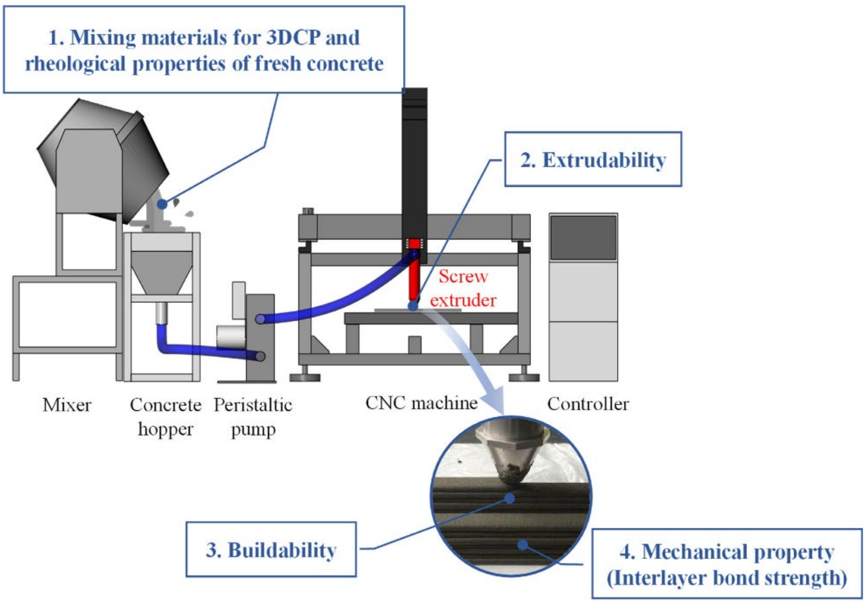

Fig. 1 Schematic description of 3DCP system (Lee et al., 2024)

For efficient pumpability, the material must exhibit low plastic viscosity to enable smooth flow under pressure, while retaining sufficient dynamic yield stress to prevent material segregation. Extrudability is mainly governed by an appropriate balance of dynamic yield stress and rheological uniformity, ensuring consistent filament deposition and dimensional accuracy. In terms of buildability, a high static yield stress is essential to support additional layers without deformation or collapse, reflecting the early-age mechanical stability of the printed structure.

As the printing process unfolds, the material undergoes a transition from a flow-dominated state to one where mechanical strength becomes the controlling factor. This shift necessitates the application of different modelling approaches, ranging from rheological frameworks to solid mechanics, to accurately describe the material's behaviour (Chang et al., 2023; Ranjbar et al., 2021).

3.1 Pumpability

Pumpability is a critical prerequisite for the effective execution of 3DCP, as it involves navigating complex flow dynamics during the transport of fresh concrete through pipes. During pumping, the material typically exhibits three distinct flow regimes (Secrieru et al., 2020; Yuan et al, 2024): plug flow, shear flow, and laminar flow. Plug flow describes the uniform movement of the concrete mass within the core of the pipe, characterized by a nearly constant velocity profile. Shear flow occurs near the pipe walls, where velocity gradients form due to friction, while the central core remains relatively undisturbed. Laminar flow is marked by a smooth, continuous velocity gradient that decreases from the centreline toward the pipe boundary.

Accurately identifying the prevailing flow regime is essential for estimating the required pumping pressure, reducing the risk of blockages, and improving overall process efficiency. These flow behaviours are strongly influenced by the material's rheological properties, especially yield stress and plastic viscosity. A high yield stress increases the initial pressure required to initiate flow, while high plastic viscosity significantly affects continuous pumping by increasing pressure loss. Furthermore, the shear-induced particle migration creates a lubrication layer near the pipe wall, characterized by lower yield stress and plastic viscosity compared to the bulk concrete, dramatically reducing interfacial friction and thus enhancing pumpability. Hence, rheological parameters such as yield stress and viscosity, along with characteristics of the lubrication layer and fluid dynamics factors like the Reynolds number, are critical to effectively predicting pumpability and ensuring efficient operation of concrete printing processes (Feys et al., 2022).

Notably, the presence and thickness of the lubrication layer are highly sensitive to mix design variables, such as the water to binder ratio and particle packing density, which in turn affect the pressure drop required along the pipe. Recent studies highlight that supplementary cementitious materials (SCMs), particularly fly ash and silica fume, can improve pumpability by enhancing the paste volume and promoting smoother particle migration, forming a more stable lubrication layer (Chen et al., 2022). However, excessive viscosity modifiers or improper aggregate grading may hinder this effect by increasing flocculation or obstructing the formation of shear zones necessary for plug flow development (Saruhan et al., 2022).

3.2 Extrudability

Extrudability is a key functional attribute in extrusion-based 3DCP, referring to the capacity of fresh cementitious material to be continuously and consistently pushed through a nozzle under controlled pressure, while maintaining its filament shape and avoiding flow instabilities, blockage, or phase separation. Reliable extrudability is essential for ensuring proper layer formation, dimensional accuracy, and interlayer bonding throughout the printing process.

Various experimental techniques have been developed to evaluate extrudability in cement-based materials. Among them, ram extrusion is the most widely used in laboratory experiments. In this method, a piston applies pressure to extrude the material through a die, serving as the basis for several theoretical models, including those developed by Benbow and Bridgwater (Benbow et al., 1987), as well as Perrot et al. (Perrot et al. 2006). In practical 3DCP systems, screw-based extrusion is more commonly employed, offering continuous material output. However, modelling these systems is more complex due to varying shear rates and pressure along the screw channel.

Extrusion behaviour is strongly governed by the rheological characteristics of cementitious materials, particularly dynamic yield stress and plastic viscosity. A high dynamic yield stress increases the risk of filament discontinuity and nozzle blockage, while elevated plastic viscosity primarily contributes to higher extrusion pressure (Rahman et al., 2024). Experimental studies indicate a near-linear relationship between extrusion pressure and plastic viscosity, especially in systems utilizing narrow or tapered nozzles, where shear-induced resistance becomes more significant. Furthermore, excessive shear rates within the screw chamber may promote accelerated structuration and thixotropic rebuilding, potentially causing flow disruption and clogging (Saruhan et al., 2022). To ensure stable and continuous extrusion, it is therefore essential to carefully coordinate nozzle geometry, shear rate distribution, and thixotropic recovery behaviour.

The incorporation of viscosity modifying admixtures (VMA) has been shown to improve filament shape retention by increasing the material's viscosity. However, this also results in a rise in shear yield stress and overall flow resistance, which can hinder extrudability. Therefore, careful optimization of admixture dosage is required to achieve a balance between extrudability and post-extrusion shape stability. In addition, the interplay among particle size distribution, aggregate gradation, and binder composition directly affects flow uniformity and the risk of segregation or phase separation during extrusion (Rahman et al., 2024).

Recent studies have also explored the use of vibration-assisted extrusion, in which oscillatory forces are applied to reduce yield stress locally during discharge (Sanjayan et al., 2021). This technique improves flowability without compromising structural stability. Moreover, the geometry of the extrusion die plays a critical role in determining extrusion performance. Cylindrical, conical, tapered, and slit-shaped dies each result in distinct pressure drops, shear stress distributions along the wall, and entry effects (Rahman et al., 2024; Saruhan et al., 2022). These factors must be carefully considered when designing an extrusion system to ensure continuous and defect-free printing.

3.3 Buildability

In extrusion-based 3DCP, buildability refers to the ability of freshly deposited layers to support the weight of subsequent layers without undergoing plastic deformation or structural instability. This performance indicator is essential to achieving vertical growth of printed elements and maintaining geometric accuracy without additional formwork. Buildability is primarily governed by two failure mechanisms: plastic yielding, which occurs when the material cannot withstand compressive stresses, and elastic buckling, a structural instability resulting from slender geometry and insufficient stiffness.

To assess buildability under these competing mechanisms, a range of analytical models has been proposed. Suiker's model (Suiker, 2018) offers a coupled approach that integrates both plastic collapse and elastic buckling, making it particularly suitable for evaluating structural stability under the accumulated weight of multiple layers. In contrast, Roussel's mixed criterion (Roussel, 2018) combines the rheological yield strength of the material with geometric stability conditions, providing a practical perspective that links fresh state material behaviour with early-age structural performance. For a more conservative estimation, Kruger's lower bound model (Kruger et al. 2019) focuses on plastic failure and relates the maximum buildable height directly to the static yield stress of the mixture.

These theoretical frameworks highlight the necessity of incorporating both material rheology and structural mechanics in buildability assessments. Rheological parameters such as static yield stress and structuration rate are crucial for preventing plastic collapse, as they determine the material's ability to resist deformation immediately after deposition. Simultaneously, the development of elastic modulus at early age becomes a controlling factor in resisting buckling, particularly in tall or slender printed structures. The time-dependent evolution of both these parameters requires precise control over material formulation and the interval between layer placements.

Recent research has extended these concepts by adapting the Mohr–Coulomb failure criterion to 3D printing concretes (Jayathilakage et al., 2020). This approach enables more accurate prediction of plastic failure in low aspect ratio geometries, which are common in layered construction. In addition, studies have shown that the elastic modulus at the time of printing is strongly influenced by the binder composition and rest time between layers, both of which affect the structural stiffness and tendency to buckling. Importantly, the transition point between plastic and elastic failure modes depends on a combination of Poisson's ratio, layer geometry, and early-age strength development, suggesting that print schedules must be aligned with material hardening behaviour to ensure structural reliability.

Beyond bulk properties, interlayer bonding also plays a significant role in buildability (Khan et al., 2024). Controlled thixotropic recovery and adequate viscosity promote strong cohesion between successive layers, improving vertical load transfer and reducing the risk of delamination or interface weakening. As such, achieving high buildability requires a comprehensive strategy that integrates material design, process control, and structural modelling.

4 Discussion on parameters affecting structural performance

The structural integrity and quality of 3D printing concrete are heavily influenced by key printing parameters, including layer deposition time, nozzle size, print speed, and standoff distance. These factors directly impact interlayer adhesion, microstructure, and mechanical performance (Zhang & Sanjayan, 2023). Layer deposition time affects bond strength between layers; longer intervals can lead to surface drying and weaker adhesion, while optimal timing maintains moisture and enhances bonding (Nerella et al., 2019). Print speed plays a role in compaction and layer bonding. Excessive speed reduces interlayer adhesion, while moderate speeds support better rheological control and interface quality (Zhang et al., 2022; Zhou et al., 2022). Nozzle size influences filament shape and contact area. Larger diameters improve buildability, whereas smaller ones enhance fibre alignment, boosting tensile and flexural strength in fibre-reinforced mixes (Khan et al., 2024). Standoff distance (nozzle height) affects compaction pressure. Higher distances reduce bonding, while lower heights improve filament merging and reduce porosity (Wolfs et al., 2019). Advanced nozzle designs with interface shaping or side trowels further improve interlayer bonding and reduce defects by optimizing filament geometry and compaction (He et al., 2021; Zhang & Sanjayan, 2023). Optimizing these parameters is essential for improving interlayer cohesion and ensuring the structural performance of 3D printing concrete elements.

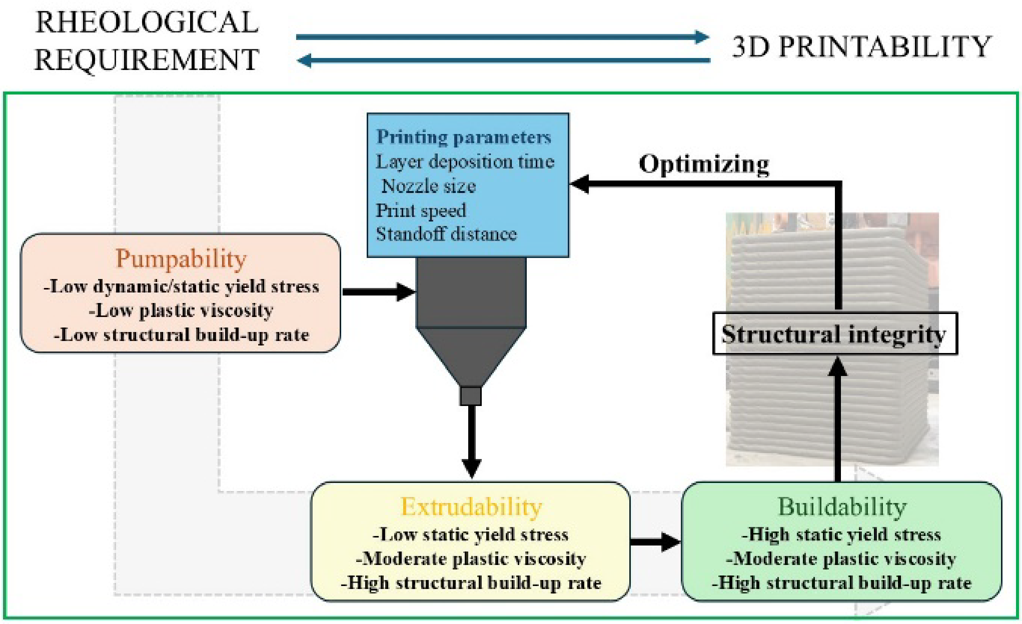

Fig. 2 Scheme for parameter requirements in 3DCP

5 Conclusions and Future Work

3DCP presents a promising solution for automated, formwork-free construction with improved design flexibility and material efficiency. The success of this technique depends on a comprehensive understanding of the rheological properties of fresh concrete and their interaction with key process parameters. This review has highlighted how parameters such as static yield stress, dynamic yield stress, plastic viscosity and thixotropy influence the main aspects of printability, including pumpability, extrudability and buildability. These properties affect not only the flow and deposition of the material but also its structural stability and the quality of interlayer bonding. Printing parameters such as nozzle geometry, print speed, standoff distance and layer deposition time also play a critical role in determining the mechanical performance of printed elements. Existing analytical models provide useful frameworks for predicting failure mechanisms and assessing structural buildability. Overall, this review underscores the importance of integrating material design with process control to achieve reliable and robust structural performance in 3D concrete printing. Future research should focus on the following areas to further advance 3DCP:

- Development of sustainable, high-performance cementitious mixtures incorporating eco-friendly supplementary cementitious materials (SCMs) and fiber reinforcements.
- Implementation of real-time characterization and adaptive control systems to dynamically optimize extrusion parameters and prevent issues such as nozzle clogging and inconsistent interlayer bonding.
- Advancement in analytical and numerical models integrating rheology, hydration kinetics, and structural mechanics to improve predictive accuracy of printed structures.
- Systematic studies on long-term durability and structural performance under realistic environmental and loading conditions, including creep, shrinkage, thermal behavior, and fatigue resistance.
- Establishment of standardized testing protocols and evaluation criteria specifically tailored for 3DCP, encouraging industry-wide adoption and ensuring quality and safety consistency.

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Data Availability Statement
Data available within the article.

Conflicts of Interest
The authors declare no conflict of interest.

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