A STREAMLINED DECENTRALISED WORKFLOW FOR OBTAINING SPECIFIC MECHANICAL PERFORMANCE AND GRADE OF 3DPC: TOWARDS THE STANDARDISATION AND INDUSTRIALISATION OF 3DCP

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Abstract. This work presents findings of ongoing experimental research on 3D Concrete Printing, aiming at rationalising the production parameters in favour of the final mechanical performance – the grade – and at the same time proposing a decentralised approach for the rapid definition of production standards and their reliable and tamper-proof distribution to streamline the obtaining of a specific 3D-Printed Concrete grade. Moving from preliminary considerations about the fragmentation of current research, we suggest approaching the standardisation problem from the basic principle of the structural requirements rather than the development of hyper-specialised materials. We propose a 2-step experiment with the creation of a Distributed Ledger Technology-based decentralised framework acting as a repository of experimental data from different production laboratories, each with its specific setup and production settings. In the first stage, the decentralised framework collects and analyses the production data, detecting different production settings and mechanical performance relations and patterns. In the second stage, the system suggests optimised production settings for obtaining the required grade. The decentralised framework constitutes the infrastructure for the definition of production standards based not only on construction requirements but also considering the variable production setups, laying the foundation for a smoother adoption of the standards.

Keywords: *3D Concrete Printing, concrete grade, industrialisation, standardisation, decentralised ledger technology.*

1. Introduction

Nearly a century after its invention, 3D Concrete Printing (3DCP) remains impractical for industrial use. The system, patented in 1944, already included key features of today's technology, such as embedding metallic mesh as the shear-resistant material within concrete. Today, despite advancements in Computer Numerical Control (CNC) machines, robotics, material science, Internet of Things (IoT), and Artificial Intelligence (AI), the lack of standardised regulations prevents 3DCP's industrial application. Additionally, hyper-specialised research aims to solve numerous 3DCP-related challenges, but it has so far failed to promote a real and systematic industrialisation of such technology, as it generally fails to address the standardisation problem. Hence, our focus is on rationalising the process so as to provide a robust workflow that could lead to more coherent and standards-compliant applications.

Through a schematization of the traditional concrete construction pipeline, we propose an equivalent scheme for 3DCP-based construction, enhanced by the adoption of Decentralised Ledger Technologies (DLT) and capable of creating a tamper-proof verification and validation system. As a multi-step and multi-disciplinary process, 3DCP entails several technical and non-technical dimensions, all subject to standardisation. However, the design-to-construction process attributes a central role to the adoption of the right concrete grade, as this property defines the mechanical performance of the material and, therefore, of the structural element, entailing structural and safety consequences.

In the design-to-construction workflow, the designer and the constructor define the structural design, giving a precise indication of the required concrete mechanical performance. The 3DCP provider, or the 3DCP-capable constructor, oversees the production of the structural elements using 3D-Printed Concrete (3DPC) with the required concrete grade. Therefore, from an industrial point of view, the first unresolved challenge of 3DCP structural applications is about being able to obtain a certain concrete grade given specific production settings and environmental conditions and its related validation based on an agreed construction code. While representing common knowledge and standard practice in the case of traditional cast-in-place concrete, the grade remains a crucial parameter to be controlled and verified in the case of 3DPC.

For standard concrete applications, the grade is determined via compression test of specimens after 28 days of curing, and it corresponds to the compressive strength expressed in megapascals (MPa). For example, M20 concrete has a compressive strength of at least 20MPa. Depending on the grade, concrete is classified as normal, standard, or high strength (Table 1). A minimum grade of M20 is recommended for reinforced concrete applications.

TABLE 1. Traditional cast-in-place concrete grade.

Mix ratio	Compressive strength	Concrete grade	
1:5:10	5 Mpa	M5	Normal
1:3:6	10 Mpa	M10	
1:2:4	15 Mpa	M15	
1:1.5:3	20 Mpa	M20	
1:1:2	25 Mpa	M25	Standard
Design mix	> 25 Mpa	> M25	Standard or High Strength

In the case of 3DCP, current national and international regulatory bodies do not provide clear and agreed-upon guidelines for such verification and standards, hence leaving a legal void that prevents adopting 3DCP as a standard building technology. In today’s interconnected society, and with the body of knowledge produced by researchers all over the world, 3DCP represents more than a local approach, but rather the outcome of a global effort, and as such, its shortcomings should be addressed (Ahmed, 2023). In this context, it appears necessary to rely on common, shared and secure workflows and technologies allowing multiple and multi-located scientists to contribute in a standardised manner. With this assumption, we propose a decentralised experimental framework which relies on the adoption of Blockchain Technologies (BTs) for the management and recording of materials preparation, specimens’ production, onsite testing, and performance validation. BCTs can support such kind of experimentations in light of their transparent nature, tamper-proof capability and potential to embed automated processes via smart contracts (Hunhevicz et al., 2022).

The choice of adopting a decentralised experimental framework is also motivated by the considerable number of tests required to obtain a representative sample of production: a single fabrication laboratory would inevitably present time, technology, environmental and materials limitations, thus being representative of a unique production scenario without scalable and universal value. With scalability being a primary goal, the involvement of other labs in different geographic locations has two requirements: 1) adopting decentralised ledger technologies (DLT); 2) following strict production guidelines for executing and monitoring all production stages, from materials preparation to 3D printing, curing, and testing.

2. Research Background and Literature Review

The industrialisation of 3DCP and its introduction into the market as an alternative to onsite concrete casting have not yet reached their expected expansion due to the insufficient development of technologies and materials, and the lack of validated and shared standards (Diks, 2019; El-Sayegh et al., 2020; Van Der Putten et al., 2022).

Attempts at standardising some of the dimensions having an impact on 3DCP processes are being made, for example the industrial application of Additive Manufacturing (AM) technology ("ISO/ASTM 52939," 2023), or the geometric properties and testing of 3DPC specimens (Cai et al., 2024).

Considering the top five high-frequency keywords from the scientific publications on 3DCP between 2014 and 2023 (Wang et al., 2024), a prevalent interest in the mechanical performance of 3DPC seems to emerge, but as already observed, the research tends to focus on very specific aspects, such as the use of admixtures, the integration of shear-resisting materials, etc.

The mechanical performance of 3DPC is affected by ink properties, concrete mixture preparation, and environmental conditions, while the hardened material is characterised by anisotropic behaviour due to the deposition of material filaments and the layered structure (Şahin and Mardani, 2023). Additionally, scholars agree on the relevance of the water-to-binder ratio (*w/b*, sometimes indicated as *w/c*, water-to-concrete) in the determination of the final concrete grade (Yu et al., 2021).

The use of Artificial Intelligence (AI) and Machine Learning (ML) for large datasets analysis and AI-inference can suggest optimised production parameters or provide indications and instructions for maintaining process quality (AlKhader et al., 2023). Large Language Models (LLM) and Multimodal Large Language Models (mLLM) can enable *adaptive 3DCP* (Di Marco and Cheung, 2025) with real-time automatic adjustments of production settings and 3D printing hardware.

The multi-disciplinarity of the process, together with the scattered research and the proposed decentralised setting, generates a concrete risk of misalignment of research topics, nomenclature, materials, and technologies, and mismatch problems in the communication and exchange of information and data, making it necessary to standardise the way such information is conveyed among the involved stakeholders. This circumstance becomes even more important in the presence of 3DCP service providers (Monroy et al., 2023); therefore, the definition of an ontology for the effective and reliable transmission of information is necessary (Han and Schaefer, 2019).

The construction industry's digital transformation is being reshaped by blockchain technology, which offers more than just incremental improvements to existing processes by enabling entirely new paradigms of decentralised governance and economic coordination (Davidson et al., 2018; Dounas et al., 2021; Hunhevicz et al., 2022). At the heart of this transformation lies blockchain's unique capacity to create trust-minimised systems that align stakeholder incentives through crypto-economic mechanisms, automate verification processes via smart contracts, and facilitate collaborative innovation across organisational boundaries. Recent advancements in blockchain technology have prompted significant interest in its potential applications within the construction sector, particularly concerning governance and standardisation challenges. Scholarly investigations have explored how blockchain's inherent features — decentralisation, immutability, and smart contract automation — could address systemic inefficiencies in construction processes. Within this broader discourse, emerging research has begun examining the intersection of blockchain and additive manufacturing, specifically 3DCP, where standardisation remains a critical barrier to widespread adoption.

Existing literature highlights the fragmented nature of 3DCP development, with research institutions, material suppliers, and construction firms operating under disparate methodologies and quality benchmarks. This lack of cohesion has led to inconsistencies in material performance, structural reliability, and process optimisation, hindering scalability. Traditional approaches to standardisation — typically centralised and slow-moving — struggle to accommodate the rapid innovation cycles characteristic of additive manufacturing. Consequently, decentralised technologies emerged as a potential solution, investigating whether blockchain's governance models could provide a more adaptive framework for knowledge sharing and compliance.

Several studies have documented blockchain's role in enhancing traceability and accountability in construction supply chains, with applications ranging from material provenance tracking to automated contract enforcement. Research by Hunhevicz et al. (2022) demonstrates how crypto-economic incentives can improve data quality in construction projects, while others have explored blockchain-based systems for real-time quality assurance in industrial applications (Zhong et al., 2020). These findings suggest that similar mechanisms could be applied to 3DCP.

Further academic inquiry has focused on decentralised autonomous organisations (DAOs) as a governance model for collaborative industries. Theoretical frameworks propose that DAOs could facilitate distributed decision-making in technical standardisation, allowing stakeholders to vote on protocol updates without centralised oversight (Hassan and De Filippi, 2021; Lombardi and Dounas, 2022; Wang et al., 2019). However, the practical implementation of such models in construction — particularly in a technology as nascent as 3DCP — has yet to be thoroughly examined.

A parallel strand of research investigates the integration of blockchain with IoT and digital twins in construction (Lee et al., 2021), emphasising automated data verification and machine learning-driven optimisation. These studies provide foundational insights into how smart contracts could validate 3DCP parameters in real time, though concrete applications remain largely conceptual.

3. Research Gaps and Research Questions

The lack of shared and validated standards entails a considerable number of research and practical challenges, resulting in an endeavour that requires a coordinated multi-stakeholder approach. Moving from the main requirement of a design-to-construction process, that is, the mechanical performance of concrete, we focus on how to standardise the production process to obtain a specific concrete grade.

After identifying the elements of the 3DCP process that are necessary to obtain a specific concrete grade, we propose a method for streamlining the adjustment of the production of 3DPC specimens according to the required concrete grade.

The hypothesis is that a decentralised framework can significantly help the definition of standards by allowing the collection of a large amount of experimental data, at the same time acting as a tamper-proof repository and distributor of standards.

This paper aims to address the following research questions:

- What properties allow for standardising the 3DCP process and obtaining a specific concrete grade?
- How can a decentralised system handle such information in favour of the definition of shared and validated standards?

4. Methodology

The methodology involves a two-phase experimental approach conducted in a dedicated robotic 3DCP fabrication lab equipped with a KUKA KR300 R2700-2 and hydraulic press for testing. In the first phase, a series of 3DPC samples is produced following international concrete standards, with key production parameters (e.g., layer deposition speed, material composition, curing conditions) precisely monitored and recorded. These samples then undergo compression testing to determine their mechanical resistance and performance grade. The resulting data — linking production parameters to the experimentally validated concrete grade — is compiled into a structured dataset and securely stored on a private blockchain to ensure traceability and immutability.

The second phase, outlined but not covered by this work, focuses on industrial application, where a target concrete grade is specified, and the corresponding optimal production parameters are retrieved from the blockchain. This phase simulates real-world construction workflows, leveraging AI-driven analysis of the dataset to recommend lab-specific printing parameters for achieving the desired 3DPC performance.

Figure 1 shows the 2-step experiment (Di Marco et al., 2025), where such parameters are monitored during the production process, and their values are stored, together with the corresponding grade, in a production package.

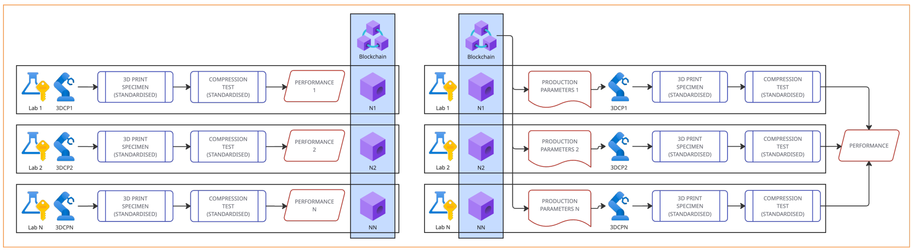

Figure 1. 2-step experiment for grade standardisation - Image created by the first author.

5. 3DCP parameters

Understanding the relation between production parameters and mechanical performance is essential to establish an efficient 3DCP process based on optimised and standardised dimensions. A benchmarking of materials and performance has been conducted, based on the 3D printing and compression testing of 3DPC specimens, and a thorough tracking of relevant parameters has been maintained, subdividing such parameters into three categories: design, environmental, and production parameters.

5.1 DESIGN PARAMETERS – SPECIMEN DESIGN

The most common cubic specimen sizes for the compression test of 3DPC are 30, 40, and 50mm (Cai et al., 2024). Depending on the nozzle diameter, these specimens consist of a single-line wall, thus showing no intralayer discontinuity.

Adopting the traditional specimen dimensions, we propose a cubic specimen with a side length of 150mm, allowing for multi-filament layers with the possibility of using a cross-ply pattern (Figure 2), in favour of a more homogeneous lateral mechanical performance (Şahin and Mardani, 2023).

Figure 2. Cubic 3DPC specimen with cross-ply pattern.

The 3D-printed cubic specimens are cut to dimensions (Figure 3) after the printing job has finished, removing the irregular superficial texture derived from the cross-ply pattern: this allows for improving the contact between the face of the specimen and the plate of the press, ensuring the best execution of the compression test.

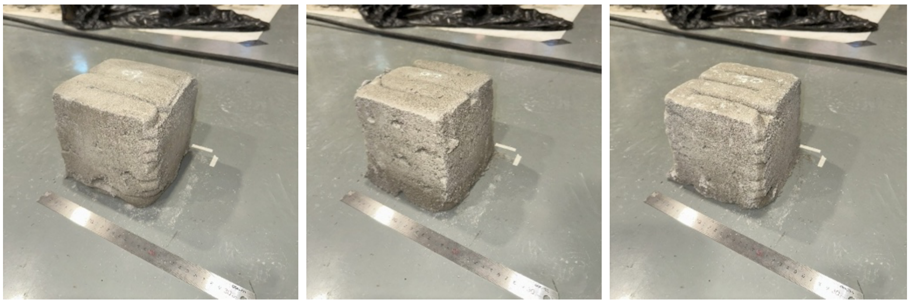

Figure 3. 3DPC specimens cut to dimensions.

5.2 ENVIRONMENTAL PARAMETERS – INDOOR CONDITIONS

Humidity and temperature affect the evaporation of water and the workability and rheology of the concrete mix, and ultimately the mechanical performance of 3DPC. Our study is limited to indoor applications, typically for prefabrication in a controlled environment. However, the methodology is scalable and applicable to outdoor applications by adding other environmental parameters, such as wind speed and direction or others.

5.3 PRODUCTION PARAMETERS – MATERIALS, SOFTWARE, HARDWARE

The ink used in our tests presents the following components: Ordinary Portland Cement (OPC), Sulphoaluminate Cement (CSA), Sand, Water Reducer (PCE Superplasticiser), Cellulose Ether (HPMC), Thixotropic Agent, and Polypropylene Fibre.

Concrete mix composition and preparation are monitored, and all parameters are annotated together with software and hardware settings (slicing parameters, robotic arm parameters, and nozzle dimensions) as summarised in Table 2, which also served as the template used for tracking 3DCP parameters.

TABLE 2. 3DCP parameters tracking

Design parameters	- Specimen shape - Specimen dimensions - Slicing
Environmental parameters	- Temperature - Humidity
Production parameters	- Ink formulation - Concrete mix - Mixer settings - Pump settings - 3D printer type - 3D printer model - 3D printer settings - Extruder settings - Nozzle size

The observation throughout the preparation of the first set of 3DPC samples shows that the parameters having the most relevant effect on the final 3DPC grade are the infill pattern and the water-to-ink ratio (hereafter w/i) in the concrete mix. The adoption of the standard cubic specimen with 150mm side and the subsequent multi-filament layer and cross-ply pattern allows for considering the anisotropic behaviour of 3DPC, and at the same time offering a solution to the varying compression strength depending on the orientation of the applied load. The mechanical strength of 3DPC is maximum for lateral load along the X direction (along the filament), minimum for lateral load along the Y direction (perpendicular to the filament) and intermediate for vertical load along the Z direction (perpendicular to the layer) (Cai et al., 2024). By alternating the filament orientation, swapping the X and Y directions in every new layer, the cross-ply pattern makes it possible to consider only two load orientations during the compression tests: vertical (perpendicular to the layers) and lateral (coplanar to the layers).

Regarding the w/i ratio, we have found that it substantially affects the 3DPC grade: a little variation of this parameter, in fact, determines a sensible increase or reduction of the grade. The optimal w/i ratio is, in turn, highly dependent on the ink composition and on the 3D printing setup.

6. 3DPC grade

The compression tests have been conducted on the first set of 60 3DPC produced specimens, alternating vertical and lateral loads (Figure 4).

Figure 4. Compression test with lateral load.

We observed a high variability of the grade depending on the w/i ratio, with the optimal value being 0.15 (15%): with this value, the 3DPC grade has been consistently M25 for both vertical and lateral loads. A w/i of 17% corresponded to a significant decrease in the grade, measured both vertically and laterally, with no specimen reaching grade M20 and with vertical grade being consistently higher than lateral grade, thus revealing an increased anisotropic behaviour despite the presence of the cross-ply pattern (Table 3).

TABLE 3. 3DPC grade with 17% w/i ratio

Specimen ID	w/i	Load orientation	Strength (MPa)
20230912-003	0.17	Vertical	17.9
20230912-004	0.17	Vertical	15.5

20230912-005	0.17	Vertical	18.0
20230912-006	0.17	Vertical	15.8
20230912-007	0.17	Lateral	5.4
20230912-008	0.17	Lateral	4.4
20230912-009	0.17	Vertical	17.9

In the latest tests, we have used a batch of expired ink and set the w/i ratio precisely to 15% to study the mechanical performance in suboptimal conditions due to ink expiration. We discovered that the lateral grade decreases significantly, never reaching M20 and with an average strength of 13.5MPa, while the vertical grade increases to an average of M35, with a minimum of M30 and a maximum of M40.

7. Production package preparation and distribution

We envision the standardisation of 3DPC as a process relying on the systematic aggregation of manufacturing and performance data into a unified digital record — the *production package*. This comprehensive file serves as the foundational element for traceability, quality assurance, and knowledge sharing among researchers and within the construction industry. By integrating the production package into a blockchain network, stakeholders gain access to an immutable, decentralised repository of verified 3DPC parameters, enabling reproducibility, compliance, and data-driven optimisation.

The production package is a structured digital file that encapsulates all critical data generated during the lifecycle of a 3DPC specimen — from design and fabrication to curing and mechanical testing. Each package contains seven core components, ensuring full transparency and replicability:

1. Design Parameters define the specimen's digital blueprint, including layer resolution and geometric tolerances.
2. Environmental Conditions document ambient factors such as temperature and humidity during printing.
3. Production Parameters record real-time operational data, including materials properties and preparation, software and hardware settings.
4. Visual Documentation provides high-resolution images of the specimen at key stages, facilitating visual quality control.
5. Curing Regimes specify time, temperature, and humidity profiles during the hardening phase.
6. Testing Results compile compressive strength measurements and failure modes from standardised lab tests.

7. Assigned grade links the specimen's performance to conventional concrete classifications.

These components are formatted into a standardised schema (Table 4) to ensure interoperability across blockchain nodes and downstream applications.

TABLE 4. Production package data scheme

Data category	Format	Use case
Design parameters	Cad/bim + json metadata	Digital replication of geometric models
Environmental data	Time series csv	Anomaly detection
Production settings	Machine logs (xml)	Process optimisation
Visual records	Jpeg/png + timestamps	Defect auditing
Curing parameters	Structured logs + time series csv	Compliance alignment
Test results	Lab reports (pdf)	Grade certification
Grade classification	Standardized tag	Regulatory alignment / benchmarking

The transition of the production package from a standalone digital file to a blockchain-anchored asset fundamentally redefines how 3DCP data is managed, shared, and utilised across the construction ecosystem. Upon completion of specimen testing, the package undergoes a structured integration process with a permissioned blockchain network, designed to address the construction industry's need for traceability, auditability, and collaborative innovation.

7.1 IMMUTABLE DATA ANCHORING AND VERIFICATION

Each production package is processed through a cryptographic hashing algorithm, generating a unique digital fingerprint that permanently links the dataset to the blockchain. This hash is embedded into a transaction block alongside metadata, such as timestamps and contributor credentials, creating an immutable audit trail. This mechanism ensures provable data integrity, critical for compliance scenarios where regulators or clients demand evidence of unaltered production records.

7.2 DECENTRALISED ACCESS AND SMART CONTRACT AUTOMATION

Unlike traditional centralised databases, the blockchain distributes copies of production packages across a network of authorised nodes (e.g., manufacturers, testing labs, and regulatory bodies). Access is governed by smart contracts — self-executing protocols encoded with predefined rules, providing stakeholders with enhanced control and hence design capabilities.

A contractor seeking to verify the grade of a 3DPC element submits a query via a smart contract, which retrieves the corresponding production package from the blockchain and cross-checks its testing results against project specifications.

A materials scientist might request all packages tagged with a specific curing regime to analyse performance trends, with the smart contract filtering and aggregating data without exposing proprietary information.

This automation reduces reliance on intermediaries while enabling real-time compliance checks and peer-to-peer data sharing.

7.3 INTEROPERABILITY FOR PREDICTIVE ANALYTICS

Standardised schemas within production packages allow AI tools to parse historical data at scale.

For instance, a machine learning model could correlate extrusion speed and ambient humidity with compressive strength outcomes, identifying optimal parameters for a target grade; flag anomalies in real-time production data by comparing live sensor feeds against blockchain-stored benchmarks, triggering corrective adjustments.

8. Discussion and Future Developments

According to the tests conducted and the results obtained, it emerges that the design parameter corresponding to the infill strategy plays an important role in the definition of 3DPC. Existing attempts at standardising the specimens for determining 3DPC grade refer to single-filament constructs that might be representative of specific applications of 3DPC, such as hollow walls or formworks. However, when considering a broader range of applications, such as bespoke free-form structural elements, the slicing method becomes paramount. Our choice of adopting the cross-ply pattern made it possible to achieve a uniform M25 grade for vertical and lateral loads, allowing for complex production scenarios and the horizontal 3D printing of layers that will be oriented vertically once the element is assembled. This, in turn, opens up the possibility of laying complex rebar layouts within the horizontal 3D-printed layers, knowing that such rebars will be working on a vertical plane, and this circumstance might contribute to the embedding of shear-resistant elements inside 3DPC constructs, one of the challenges of current 3DCP production.

The w/i ratio shows a direct effect on the 3DPC grade: in our production setting, the optimal value of 15% maximises the grade and minimises the anisotropic behaviour of the specimen. However, this parameter is strictly related to the ink composition, the 3D printing hardware and the production tools (mixer and pump); therefore, more testing is required to define whether our findings are generalisable and scalable or remain confined within our production setting. The involvement of other 3DCP labs, as per the above description, will help clarify this aspect.

One relevant finding regards the consistent good performance and grade of 3DPC for vertical load, which is maintained in sub-optimal conditions such as wrong w/i values or expired ink. This further strengthens our studies on stress-informed non-planar slicing, aiming at capitalising on the anisotropic behaviour of 3DPC for better structural performance.

This study conceptualises a blockchain as a stigmergic information layer (Dounas et al., 2022), utilising smart contracts and tokenisation to enable collective digital factories in construction. The proposed framework focuses on orchestrating a network of research labs, material scientists, and digital tools for building design, though its application can be extended to the entire AEC lifecycle. Our research specifically leverages this model of stigmergic coordination to accelerate international research in 3D Printed Construction (3DPC). The intrinsic global and collaborative nature of this endeavour makes it an ideal use case for a decentralised framework. A key goal is to facilitate the foundational work for establishing standardised codes and practices for building with the 3DPC technology. We posit that this model of coordination, powered by cryptoeconomics, is better suited to the construction industry's fragmented nature than current organisational modes, and it better supports the expansion of the concept of Decentralised Science.

As planned in the 2-step experiment, the future developments will focus on:

- Studying the correlation between w/i and ink composition.
- Uploading production packages and creating the production dataset, deploying the whole BTs-based process.
- Analysing the production dataset with AI.

9. Conclusions

In this work, we implemented the first part of our 2-step experiment for the streamlining and standardisation of 3DPC grade. Based on the experimental data from compression tests on 3DPC specimens, we verified the importance of the w/i ratio during the preparation of the concrete mix to maximise the mechanical performance, and we proposed the adoption of the cross-ply infill strategy for the slicing to reduce the anisotropic behaviour of the construct. We then described the encoding of the production package, in preparation for the intermediate phases of the experiment, which will consist of using BCTs for creating the production dataset and AI for the analysis and optimisation of parameters and grade.

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