DEFINING A BLOCKCHAIN-VERIFIED SPECIMEN PASSPORT FOR 3DCP STANDARDISATION

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Abstract

3D Concrete Printing (3DCP) adoption is limited by prescriptive standards that cannot accommodate interdependent process parameters (e.g., nozzle speed, layer height, curing) affecting mechanical performance. Current approaches lack a tamper-proof, end-to-end linkage between production parameters and mechanical outcomes. We propose a blockchain-verified 3D-Printed Concrete specimen passport, defining its data schema, smart-contract logic, and integration with performance-based standardisation. The passport records production process, mechanical profile, and a 28-day compressive strength grade. Blockchain's immutable ledger and smart contracts automatically verify performance claims and assign 3DCP grades, enabling flexible, auditable certification. This provides a foundational reference for data-driven 3DCP compliance, fostering industrial adoption.

Introduction

The construction industry faces a digital transformation, driven by the convergence of advanced manufacturing technologies, digital information systems, and distributed ledger technologies (Lavagna et al., 2023; Samarasinghe and Wood, 2021). Among these innovations, 3DCP represents a paradigm shift in construction methodology, offering unprecedented design freedom, material efficiency, and potential for automation (Buswell et al., 2018). Unlike conventional cast concrete, where material properties can be reasonably predicted from standardised mix designs and controlled curing conditions, 3DPC mechanical properties are determined by a complex interplay of process parameters, including extrusion pressure, printing speed, layer deposition timing, and environmental conditions, that directly influence the mechanical performance of the final element (Wolfs et al., 2019). This variability, particularly affecting the interlayer adhesion, represents a fundamental challenge to structural certification and has been identified as a primary obstacle to the integration of 3DCP into regulated construction practice (Di Marco et al., 2025; Diks, 2019; Van Der Putten et al., 2022).

The general approach to traditional construction standardisation is based on the required concrete performance, which depends on design and operational conditions and is obtained through corresponding concrete mix variation; however, traditional quality assurance methods, developed for relatively simple casting processes, lack the granularity, transparency, and immutability required to establish robust traceability and stakeholder trust in digitally fabricated construction elements (Elghaish et al., 2023). Current standardisation efforts (ICC-ES, 2022; ISO/ASTM, 2023) provide foundational quality assurance requirements but do not yet offer a mechanism for immutable, end-to-end traceability of process parameters to performance outcomes. Therefore, the establishment of a unified, verifiable framework for certifying the mechanical performance and production integrity of additively manufactured concrete elements must be framed in a flexible standardisation paradigm, due to the already mentioned extreme variability of the process, and entail a layer of transparency, auditability, and traceability.

Blockchain technology, originally developed as the underlying infrastructure for cryptocurrencies, has emerged as a promising solution for addressing trust, transparency, and traceability challenges across various industries (Li et al., 2019; Turk and Klinc, 2017). In the construction sector, blockchain applications have been explored for supply chain management, contract execution, and information flow coordination (Darabseh and Poças Martins, 2023; Ye et al., 2023). The technology's core characteristics, decentralisation, immutability, transparency, and cryptographic security, align closely with the requirements for robust quality assurance in advanced manufacturing contexts.

The concept of digital passports for construction materials has recently gained traction as a mechanism for documenting the lifecycle history of construction materials and components, particularly in the context of circular economy initiatives (Senarathne et al., 2025; Trubina et al., 2024). Material passports serve as comprehensive digital records that capture information about material composition, origin, processing history, and performance characteristics, enabling informed decision-making regarding reuse, recycling, and end-of-life management (Kc et al., 2025). The EU's Digital Product Passport (DPP) (Damvakeraki and Vlachos, 2024), mandated by the Ecodesign for Sustainable Products Regulation (ESPR), is redefining product information management for construction products by requiring standardised, machine-readable digital records that accompany products throughout their lifecycle.

Stakeholder studies have identified improved traceability and resource efficiency as key benefits, alongside integration with Building Information Modelling (BIM) (Ruismäki et al., 2025). Blockchain-based material passport systems have been proposed to address the unreliability of centralised databases in construction's dispersed supply chain, with researchers arguing that blockchain enables decentralised, transparent, and immutable information management (Kc et al., 2026). Furthermore, blockchain has been explored for additive manufacturing traceability, including cloud 4D printing service platforms and digital twin creation for trusted data provenance (Liu et al., 2025).

Building on these foundations but focusing specifically on 3DCP specimen certification within a performance-based standardisation framework—a context not yet addressed in the literature—this paper introduces a blockchain-verified material passport specifically designed for 3DPC specimens. The proposed system cryptographically anchors a comprehensive data record that spans from digital design through material sourcing to real-time fabrication monitoring and final performance validation. The 3DPC specimen passport constitutes the cornerstone of a performance-based standardisation framework. By creating an immutable and auditable chain of custody, the system addresses the core challenges of 3DCP standardisation while mitigating information asymmetry among stakeholders.

Without a digital passport system for 3DCP, the construction industry faces several foreseeable consequences: each printed element would require case-by-case regulatory approval, significantly delaying project timelines and increasing costs; the lack of tamper-proof traceability would enable data manipulation, undermining trust among clients, insurers, and regulators; performance data from one print batch could not be reliably linked to subsequent batches, preventing continuous quality improvement and statistical process control; the construction sector would miss the opportunity to align with emerging EU Digital Product Passport regulations, which are rapidly redefining supply chain transparency for construction products.

Related work

Standardisation paradigms for 3DCP

The effective management of industrial production necessitates a strong approach to standardisation, which can fundamentally be characterised by two distinct philosophical paradigms: prescriptive and flexible.

The prescriptive approach is grounded in the principles of scientific management and statistical control (Shewhart, 1930). This paradigm seeks to achieve uniformity, interchangeability, and repeatability by specifying precise dimensions, values, tolerances, and processes. It operates on the principle that variation is a primary source of quality defects. The primary objective of this approach is to eliminate deviations and ensure perfect adherence to predefined specifications. This is illustrated by models such as Technical Specifications, which offer formal, detailed descriptions of requirements (ISO/IEC, 2021), and Geometrical Product Specifications (GPS), an international standards system that defines geometrical features—including form, position, and size—on technical drawings with clarity (Henzold, 2021; ISO 8015, 2011).

The second paradigm adopts a flexible approach, guided by systems theory and the necessity for strategic adaptability (Baldwin and Clark, 2000; Sanchez and Mahoney, 1996). This approach establishes clear goals, performance criteria, and interfaces while allowing considerable autonomy in the methods used to achieve these objectives. Its purpose is to ensure interoperability and alignment of goals across diverse and dynamic production environments without hindering innovation. A prominent model in this regard is Performance-Based Standards, which define the required functional outcomes without dictating specific technical solutions, thus fostering innovation in design and materials. (Foliente, 2000).

Prescriptive standards are primarily applied to critical, high-volume, or safety-sensitive components to ensure a fundamental level of quality and interchangeability. In contrast, flexible standards operate at the system and architectural levels, fostering product diversity, process innovation, and adaptability to change. This hybrid approach, integrating the rigidity of prescriptive models with the flexibility of adaptive models, serves as a hallmark of strong and competitive industrial operations (Sanchez and Mahoney, 1996).

Blockchain technology in construction supply chains

Blockchain technology has attracted significant attention from the construction sector as a potential solution to longstanding challenges related to information management, trust, and coordination among fragmented stakeholders (Wilson et al., 2024). Li et al. conducted a systematic review of blockchain applications in the built environment and construction industry, identifying key use cases including supply chain management, contract execution, and asset lifecycle management (Li et al., 2019). Their conceptual models highlight blockchain's potential to address information asymmetry, reduce transaction costs, and enhance transparency across construction project networks.

Turk and Klinc explored the potential of blockchain technology for construction management, emphasising its ability to create immutable transaction records and enable automated contract execution via smart contracts (Turk and Klinc, 2017). Their work identified several promising application areas, including payment automation, supply chain traceability, and quality documentation. However, they also noted significant challenges related to scalability, interoperability, and the need for industry-wide standards.

More recent research has focused on practical implementations and integration frameworks. Darabseh et al. presented a novel framework for blockchain orchestration and implementation in construction, developing a blueprint for blockchain applications using

Hyperledger Firefly (Darabseh and Poças Martins, 2023). Their work provides practical perspectives on infrastructure requirements and deployment strategies, building upon earlier Ethereum-based implementations. Wilson et al. proposed a multilayer blockchain framework for provenance tracking in construction supply chains, addressing critical challenges in verifiability, scalability, privacy, and interoperability through a privacy-centric solution that combines decentralised and centralised storage (Wilson et al., 2024).

Material passports and circular economy

Material passports have emerged as a critical tool for enabling circular-economy practices in the construction sector, providing comprehensive documentation of material characteristics, origins, and lifecycle histories. Trubina et al. conducted an in-depth analysis of digital technologies and material passports for circularity in buildings, highlighting the significant potential of integrating material passports with BIM, artificial intelligence, scanning technologies, blockchain, and the Internet of Things (Trubina et al., 2024). Senarathne et al. developed a standardised materials passport framework to unlock the full circular potential of the construction industry, incorporating technologies such as BIM, blockchain, QR codes, and radio-frequency identification (Senarathne et al., 2025). Dounas et al. introduced an innovative approach using Non-Fungible Tokens (NFTs) on the blockchain to build components, creating a digital infrastructure layer that can integrate with AEC supply chains (Dounas et al., 2021). Their work on non-fungible building components demonstrates how smart contracts can enable material passports and circular economies, providing an infrastructure for whole-life-cycle BIM and the digital encapsulation of value in architectural design.

3D printed concrete–quality control and standardisation challenges

The field of 3D printed concrete has experienced rapid growth over the past decade, yet significant challenges remain in quality control and standardisation. Buswell et al. provided a comprehensive roadmap for 3DPC research, identifying key technical challenges including material development, process control, structural performance prediction, and the development of testing protocols and standards (Buswell et al., 2018). A critical challenge in 3DPC quality assurance is the influence of process parameters on interlayer adhesion, which directly affects the mechanical performance and structural integrity of printed elements. Wolfs et al. investigated the hardened properties of 3D printed concrete, specifically examining how process parameters influence interlayer adhesion (Wolfs et al., 2019). Their research demonstrated that factors such as time gap between layer deposition, printing speed, and material rheology significantly affect bond strength between layers, introducing variability that must be carefully controlled and documented for structural applications. Di Marco et al. advanced the field by developing stress-informed non-planar slicing strategies for 3D concrete printing, demonstrating how computational design approaches can optimise print paths to enhance structural performance (Di Marco et al., 2025). Their work highlights the complex relationship between digital design, process execution, and final mechanical properties, underscoring the need for comprehensive documentation systems that can capture this entire chain of causality. In another work, Di Marco et al. outlined a list of 3DCP process parameters that contribute to defining the mechanical performance and grade of 3DPC (Di Marco and Cheung, 2025). The 3DPC standardisation challenge extends beyond technical testing protocols to encompass broader issues of certification, liability, and regulatory acceptance. Traditional concrete standards, developed for cast-in-place and precast applications, do not adequately address the unique characteristics of layer-by-layer additive manufacturing. The absence of established standards creates uncertainty for designers, contractors, and regulatory authorities, hindering the technology's adoption in structural applications.

Research gaps, aims, and objectives

The lack of a shared, validated standardisation framework undermines the industry's adoption of 3DCP, constituting the principal research gap. Working towards a hybrid standardisation model, our broader research endeavour proposes adopting a blockchain-enabled, decentralised framework to collect production reports, detect production-to-grade patterns, and derive, validate, and distribute production standards. This paper focuses exclusively on the foundational first objective: to define a 3DPC specimen passport.

Methodology

A hybrid approach at the intersection of design science methods and decentralised science is adopted, i.e. the recording of artefacts and governance onto blockchains for the production of new knowledge. A new blockchain-verified 3DPC specimen passport is built on a multi-layered architecture that integrates a digital twin for performance prediction and optimisation, blockchain storage, smart contract execution, and a user interface. Its architecture follows principles established in recent blockchain for construction applications (Darabseh and Poças Martins, 2023; Wilson et al., 2024), while incorporating specific adaptations for the unique requirements of 3DPC quality assurance.

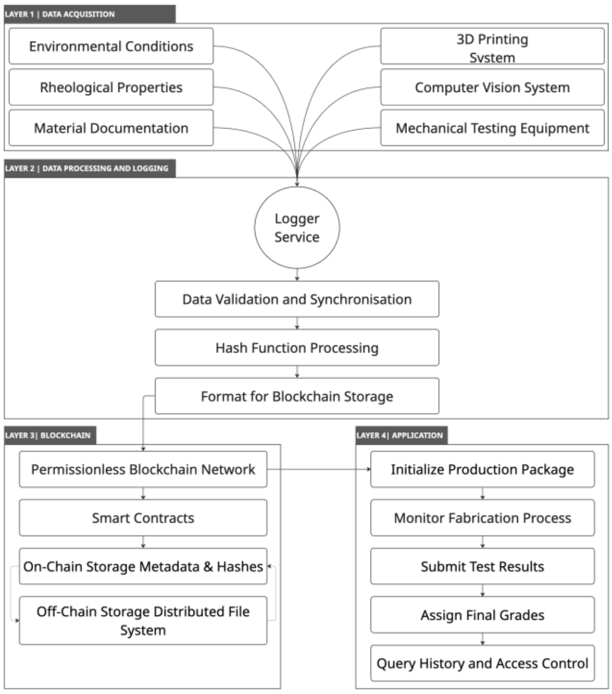

Figure 1: Framework layered structure

The system comprises four primary layers (Figure 1):

- Data Acquisition Layer: This layer encompasses all data sources that capture information about the 3DPC specimen fabrication process. It includes material batch documentation, in-line rheology monitoring, environmental conditions monitoring during printing and curing, machine control data from the robotic printer, computer vision imaging for geometric quality assessment, and mechanical testing conditions and results for performance validation.
- Data Processing and Logging Layer: A dedicated Logger Service processes raw sensor data, synchronises timestamps, performs data validation, and formats information for blockchain storage. This layer implements hash functions for large data objects (such as G-code files and vision data) to enable efficient on-chain storage while maintaining data integrity verification capabilities.
- Blockchain Layer: The core of the system utilises a permissionless blockchain network to store specimen passport data and execute smart contracts. Following best practices for construction applications (Ye et al., 2023), the system employs a hybrid on-chain/off-chain storage strategy: critical metadata and cryptographic hashes are stored on-chain, while large data objects are stored in distributed file systems, with their hashes recorded on the blockchain for verification.
- Application Layer: User-facing interfaces enable stakeholders to initialise production packages, monitor fabrication progress, submit test results, assign final grades, and query the complete history of any 3DPC element. Access control mechanisms ensure that different stakeholders have the appropriate permissions to view and modify data.

Study

An extensive material characterisation campaign with 60 cases of specimen tracking (an excerpt of the results is shown in Table 1) conducted in our robotic workshop, allowed to obtain a precise understanding of the connection between process parameters and the final 3DPC grade.

Table 1: Specimen Tracking and Grade

Specimen ID	250612-004	250612-001
Temperature (°C)	23.9	23.9
Humidity (%RH)	82.8	82.8
Concrete (kg)	82.3	99.5
Water (l)	12.35	14.9
Added Water (l)	0	0
w/i	0.15	0.15
Load orientation	Parallel	Perpendicular
Strength (MPa)	16.4	37.0
Grade	M15	M35

With reference to Figure 1, this was equivalent to implementing the data acquisition layer of the framework.

Framework overview

Beyond the basic material passport, our system manages the whole lifecycle of the 3DPC specimen, from production process to mechanical tests. The framework is purpose-built for construction 3DCP, addressing the issues of data manipulation, production logs can be altered after a failure; lack of independent verification – a single party often certifies its own prints; fragmented traceability, material provenance, process parameters, and test results are stored in disconnected systems, making root-cause analysis nearly impossible.

The material passport for 3DPC specimens is structured as a comprehensive Production Package containing 13 distinct information elements (Table 2), each serving a specific role in establishing traceability and enabling quality verification.

Table 2: Specimen Passport

Information	What it indicates
Production Package ID & Metadata	A unique identifier for the specific print job and its basic context.
Raw Material IDs & Certificates	The specific batch and origin of constituent materials (cement, aggregates, admixtures).
Target Mix Design	The intended material composition (e.g., water-to-cement ratio, admixture doses).

Target Rheological Properties	The desired workability and printability of the concrete (yield stress, viscosity).
Print G-code (Digital File Hash)	The exact instructions for the robotic printer's toolpath.
Environmental Targets	The intended ambient conditions (Temperature, Relative Humidity) for the print.
In-Process Sensor Data	The real-time state of the material and process (pressure, flow rate, actual rheology).
In-Process Vision & Scan Data	The visual and geometric quality of the print during fabrication (bead shape, layer alignment).
Mechanical Performance Data	The achieved structural properties of the printed element (compressive/flexural strength).
Final Assigned Grade	A holistic quality score (e.g., Grade M20) for the finished element.
Final Certification Hash	A digital seal that locks the package and confirms its integrity and completeness.

This structure draws upon material passport frameworks developed for circular construction (Senarathne et al., 2025; Trubina et al., 2024), but extends them with additive-manufacturing-specific fields required by emerging standards (ICC-ES, 2022; ISO/ASTM, 2023).

The experimental implementation of the decentralised material passport system for 3DPC samples is designed using blockchain technology to ensure immutable data provenance and transparent validation processes. The system architecture comprises three core smart contracts deployed on an Ethereum Virtual Machine (EVM)-compatible blockchain, integrated with the InterPlanetary File System (IPFS) for distributed data storage. This hybrid approach balances the need for permanent, tamper-proof record-keeping on the blockchain with the practical requirements for storing large volumes of scientific data off-chain.

The **ProductionPassportNFT** contract serves as the central registry, implementing the ERC-721 non-fungible token standard to create unique digital identities for each concrete production run. The **ValidationRegistry** contract implements a decentralised validation mechanism that requires consensus among multiple independent validators, addressing the critical need for peer review in scientific data. The **DataProvenance** contract maintains a comprehensive chain of custody, tracking materials from sourcing through final testing to ensure complete traceability of the production process.

The architecture follows a modular design principle, with each smart contract addressing a specific aspect of the material passport lifecycle (Figure 2). This modular architecture provides several advantages for scientific research collaboration. First, it enables different laboratories to participate in the ecosystem without requiring a central coordinating authority. Second, it allows each contract component to evolve independently as standards and requirements evolve. Third, it facilitates regulatory compliance by clearly separating concerns for data certification, validation, and provenance tracking. Fourth, it enables integration with existing Laboratory Information Management Systems (LIMS) through well-defined interfaces.

ProductionPassportNFT smart contract

The ProductionPassportNFT contract uses the OpenZeppelin ERC-721 implementation, providing the foundational framework for creating and managing production passports as non-fungible tokens. Each NFT represents a single production run and contains metadata linking on-chain records to off-chain scientific data stored on IPFS. The use of the ERC721 NFT standard provides inherent transferability, enabling production passports to be licensed or transferred between institutions while maintaining complete provenance of ownership. The contract addresses a fundamental challenge in scientific data management: how to create permanent, tamper-proof records of experimental work while accommodating the iterative nature of scientific workflows. Unlike traditional database systems, where records can be modified or deleted, blockchain-based records are immutable once finalised. However, the contract recognises that scientific data often requires revision before final publication—preliminary results may need correction, additional tests may provide new insights, or methodological improvements may necessitate data updates. The contract resolves this tension through a versioning system that allows updates before finalisation while ensuring absolute immutability after certification. The NFT standard ensures global uniqueness and verifiable ownership history. In construction, this enables a digital chain of custody – an auditor can see who minted, validated, and currently holds the passport.

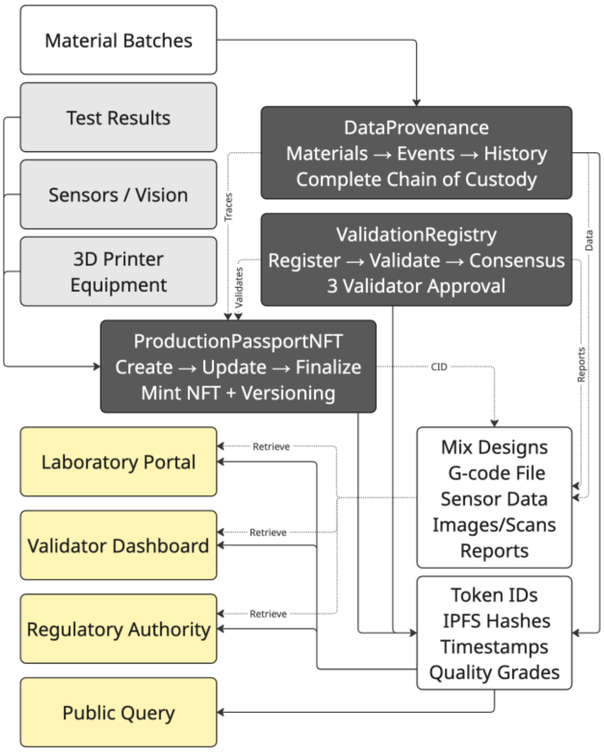

Figure 2: Blockchain-based System Architecture

Three mappings maintain contract state: passports maps token IDs to passport data structures, packageIdToToken enables lookup of token IDs by human-readable package identifiers, and _tokenIdCounter maintains the next available token ID for minting. Events are declared for all state-changing operations, enabling off-chain applications to efficiently monitor contract activity without polling every transaction.

ValidationRegistry smart contract

The ValidationRegistry contract implements a multi-validator consensus mechanism that replicates peer-review processes in scientific research (Lombardi et al., 2020). Unlike centralised validation systems, where a single authority determines data validity, this contract requires consensus from multiple independent validators, reducing bias and increasing trust in validated results. Requiring consensus among three independent validators (e.g., two accredited labs + one owner's engineer) replicates academic peer review. Collusion becomes harder, and the system provides a publicly auditable record of who approved what and when.

The architecture addresses several challenges inherent in decentralised validation. First, it must prevent collusion where validators coordinate to approve invalid data. The three-validator requirement increases the cost of such collusion and makes it more likely that at least one validator will act honestly. Second, it must maintain validator accountability while preserving the ability for legitimate criticism. The reputation scoring system provides a quantitative measure of validator reliability without creating barriers to participation. Third, it must balance transparency (all validations are publicly recorded) with practicality (validators are not penalized for disagreement with the eventual consensus).

DataProvenance Smart Contract

The DataProvenance contract implements comprehensive chain-of-custody tracking for materials and processes, addressing the critical need for traceability in construction materials. Unlike validation (which assesses quality) or certification (which attests to final results), provenance tracking creates a minute-by-minute history of everything that happened during production. This granular tracking serves multiple purposes: it enables root-cause analysis when quality issues arise, provides evidence of regulatory compliance, supports continuous improvement through statistical analysis, and increases transparency for end users who want to understand exactly how their concrete was manufactured.

The described blockchain-based architecture recognises two distinct types of provenance data that require different tracking mechanisms. Material provenance tracks the sources and certification of raw materials. These two provenance types are complementary: material provenance ensures quality inputs, while process provenance ensures proper handling of those inputs.

Summary of scientific rationalisation.

Each design decision is driven by a documented weakness in current 3DCP practice:

- NFT identity → solves counterfeit or duplicate batch records.
- Multi-validator consensus → solves the single-point-of-trust problem.
- Granular provenance → solves the traceability gap in layer-wise failures.
- Hybrid IPFS/blockchain → solves the data volume vs. immutability trade-off.
- Versioning → solves the tension between iterative research and final compliance.

Discussion and conclusions

This work is a fundamental part of the broader general aim to establish a flexible standardisation paradigm for 3DCP, encompassing diverse material choices and hardware configurations, and advocating the adoption of a decentralised framework underpinned by blockchain technology to enable verifiable compliance and traceability whilst fostering innovation. In this context, the 3DPC specimen passport enables traceability and auditability of different material choices and hardware configurations.

The introduction of a 3DPC specimen passport, as proposed in this study, represents a pragmatic step towards reconciling innovation and accountability in digital fabrication. This digital identity, encompassing the complete lifecycle of a printed element, from specific ink recipe and admixture ratios to hardware configuration and environmental conditions, shifts the paradigm of quality assurance to verifiable parameters and required performance. It functions as a cornerstone for enhanced traceability and auditability, creating an immutable record that moves beyond batch-level documentation to unit-specific provenance, enabling a flexible, performance-based standardisation model. Rather than enforcing uniformity, the passport system accommodates heterogeneity in materials and hardware by recording these variables as intrinsic data points within a compliance framework. Rather than mandating identical processes (prescriptive standardisation), this flexible standardisation defines permissible performance envelopes and requisite data integrity; notably, this approach allows connecting 3DCP to existing standards (e.g., conventional concrete grade). A printer using a novel geopolymer and another using a traditional cementitious mix can both be deemed compliant if their respective passport data demonstrate that the final printed specimen meets the same structural and durability benchmarks. This fosters an ecosystem where technological diversification and experimentation are not hindered by standardisation but are instead its documented foundation.

In conclusion, the specimen passport is posited as an enabler of a responsive, evidence-based regulatory environment. By providing a mechanism to audit performance against specific production choices, it allows standardisation to evolve from a restrictive checklist into a dynamic framework that actively supports the tailored and innovative application of 3DCP technology.

Limitations and future work

The current implementation of the 3DPC specimen passport relies on manual input of process data; however, the reliable, auditable collection of process data should be ensured by adopting digital technologies and IoT equipment. Furthermore, the integrity of the data chain, from sensor to passport must be safeguarded, potentially through blockchain or other distributed ledger technologies, to prevent tampering and establish trust. Widespread adoption will also require industry-wide agreement on the minimal dataset for a viable passport, the definition of a 3DCP ontology, and its integration into existing BIM and quality management workflows, highlighting the current interoperability gaps include missing LIMS integration, material-type standardisation, and BIM connectivity. In the current stage, the preliminary identification of process parameters relevant to the determination of mechanical performance was finalised, based on material characterisation campaigns, and the design of the system architecture and smart contracts has been completed. The next stage will consist of embedding computer vision data in the implementing the blockchain; therefore, no EVM platform has been chosen nor tokenisation mechanism was presented in this paper. Future work will prioritise Layer 2 (Figure 1) deployment for cost reduction, governance token implementation enabling decentralised control and validator rewards, automated reputation systems, cross-chain accessibility, data marketplace integration, API development for existing systems, and regulatory pilot programs demonstrating compliance benefits and practical viability.

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