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Performance Modeling of 3D Printed Structural Beams Using Low-Carbon Cementitious Composites

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Abstract
The integration of low-carbon cementitious composites with 3D printing technology offers a promising pathway toward reducing the environmental impact of construction while maintaining structural integrity and performance. This study presents a comprehensive review of performance modeling strategies for 3D printed structural beams fabricated using low-carbon cementitious materials, focusing on simulation-based optimization and artificial intelligence (AI) applications. With the construction industry accounting for nearly 38% of global CO_2 emissions, there is a critical need to develop and assess sustainable materials and digital fabrication methods that support global carbon-reduction targets. The paper evaluates a range of low-carbon cementitious composites, including fly ash-based geopolymer blends, recycled aggregate concretes, and limestone calcined clay cement (LC^3), analyzing their mechanical properties, printability, and environmental profiles. Emphasis is placed on how rheology, buildability, and interlayer bonding influence structural beam performance under flexural, compressive, and dynamic loads. Advanced numerical simulations including finite element analysis (FEA), topology optimization, and parametric design tools are reviewed for their role in predicting deformation, stress distribution, and failure modes in 3D printed beam geometries. Furthermore, the review explores emerging AI and machine learning frameworks used to predict mechanical behavior and optimize mix designs based on large datasets of material compositions and structural parameters. AI models such as artificial neural networks (ANN), support vector machines (SVM), and random forest regression are assessed for their accuracy and generalizability in structural prediction and lifecycle performance modeling. Case studies from recent experimental and computational research are synthesized to highlight best practices, practical challenges, and gaps in current modeling approaches. The review concludes by identifying opportunities for hybrid digital-physical testing environments, real-time monitoring, and sustainable design automation. By bridging material science, structural engineering, and digital fabrication, this work advances a high-performance, low-carbon framework for the next generation of sustainable construction components.

Keywords: 3D Printing, Low-Carbon Cementitious Composites, Structural Beams, Performance Modeling, Finite Element Analysis, AI, Machine Learning, Digital Fabrication, Sustainability, Green

1. Introduction
The construction industry remains one of the largest contributors to global carbon emissions, responsible for nearly 40% of total energy-related emissions through building operations and the production of construction materials. Among these materials, cement plays a particularly significant role due to its high embodied carbon content and widespread use in structural applications. As the global community accelerates efforts to combat climate change and transition toward sustainable development, there is a growing imperative to rethink how buildings and infrastructure are designed, constructed, and maintained. This has led to a surge of interest in sustainable alternatives to conventional construction practices, including the adoption of low-carbon cementitious composites and digital fabrication techniques such as 3D printing (Abayomi, *et al*., 2022, Ojika, *et al*., 2022, Oyeyemi, 2022).

Modern infrastructure demands structural components that are not only durable and high-performing but also environmentally responsible. Traditional cast-in-place or precast elements often involve high material consumption, complex logistics, and significant labor inputs. In contrast, 3D printing offers a more efficient, precise, and material-conscious approach to constructing structural elements such as beams, columns, and slabs. When combined with low-carbon cementitious composites formulations incorporating industrial byproducts, supplementary cementitious materials, or alternative binders the result is a transformative method of construction that reduces both the environmental footprint and the complexity of conventional building processes (Abdul, *et al*., 2023, Ojika, *et al*., 2023, Otokiti, *et al*., 2023).

The convergence of additive manufacturing and low-carbon materials has introduced new variables into structural design, requiring robust analytical tools to understand and predict the behavior of 3D printed elements under load. Unlike conventionally poured concrete, printed components may exhibit anisotropic properties, layer-dependent weaknesses, and unique failure modes influenced by print path, interlayer bonding, and curing conditions. As a result, performance modeling becomes an essential part of the design and validation process. It enables engineers to simulate structural behavior, optimize material usage, and ensure safety and reliability before physical testing or implementation (Abiola-Adams, *et al*., 2021, Nwangele, et ak., 2021).

This study aims to investigate the performance modeling of 3D printed structural beams fabricated using low-carbon cementitious composites, with the goal of identifying key factors that influence strength, stiffness, and failure mechanisms. By bridging material science, computational modeling, and structural engineering, the research contributes to the advancement of sustainable, high-performance infrastructure in an era defined by environmental responsibility and technological innovation (Adelusi, *et al*., 2023, Ojika, *et al*., 2023).

2.1 Methodology

The methodology adopted for this study integrates simulation, material testing, and data analytics to model the structural performance of 3D-printed beams composed of low-carbon cementitious composites. The process begins with an extensive literature review of advanced cementitious formulations, additive manufacturing processes, and reinforcement strategies. Insights were drawn from works such as Baduge *et al*. (2021) and Gebhard *et al*. (2021) to identify the mechanical behavior, printability, and interlayer bonding characteristics of materials used in similar contexts. These references informed decisions on material mix, layer height, reinforcement patterns, and design geometries relevant to performance modeling.

The next stage involves the 3D printing of beam specimens using optimized low-carbon cementitious mixes. Printing was conducted with attention to factors such as nozzle pathing, extrusion rate, and curing protocols to ensure print quality and structural consistency. Concurrently, material characterization tests were carried out to determine mechanical properties such as compressive strength, flexural strength, modulus of elasticity, and fracture toughness, following ASTM standards. This data serves as critical input for the computational modeling stage.

Subsequently, a finite element model (FEM) was developed using simulation tools informed by insights from Adeleke *et al*. (2021, 2024) and Adewoyin *et al*. (2023), who have advanced the use of intelligent monitoring and precision modeling in mechanical and structural systems. The FEM incorporated anisotropic material behavior to reflect the layer-wise build process of 3D printing and accounted for potential defects such as voids and layer misalignments. Load simulations were performed under varying conditions—static, dynamic, and cyclic—to replicate real-world structural demands.

To validate the simulation results, experimental performance tests were conducted on the printed beams, and the outcomes were compared with the FEM predictions. Key parameters for comparison included peak load, displacement, failure mode, and energy absorption. Where deviations were found, model calibration was performed using inverse parameter estimation and iterative mesh refinement.

Advanced data analytics techniques were deployed using the conceptual guidance of Abayomi *et al*. (2022) and Abdul *et al*. (2023), who proposed real-time analytics frameworks in cloud-optimized systems. Statistical error metrics such as root mean square error (RMSE), mean absolute percentage error (MAPE), and R-squared values were used to assess the predictive accuracy of the FEM models against experimental data.

Finally, performance modeling results were analyzed to evaluate the suitability of low-carbon composites for structural applications. Factors such as weight-to-strength ratio, ductility, sustainability impact, and cost-efficiency were analyzed. The study concludes with recommendations for scaling up the application of such composites in public infrastructure, incorporating AI-powered design optimization as suggested by Ogunnowo *et al*. (2024) and Ojika *et al*. (2023).

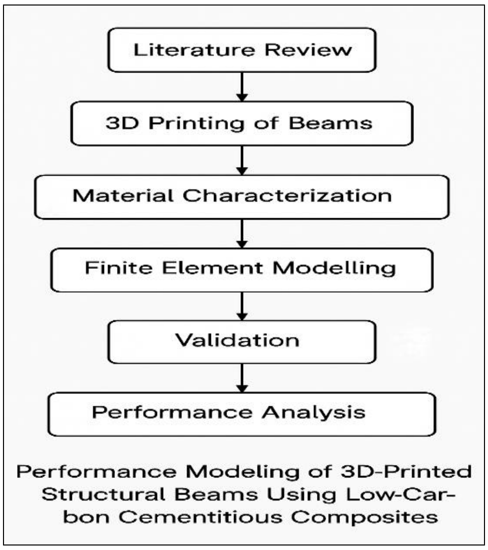

Fig 1: Flow chart of the study methodology

2.2 Low-Carbon Cementitious Composites: Material Overview

Low-carbon cementitious composites are a class of materials developed to reduce the environmental footprint of conventional Portland cement-based construction while maintaining or enhancing structural performance. These materials incorporate supplementary cementitious materials (SCMs), alternative binders, or recycled aggregates to significantly reduce the embodied carbon associated with cement production. In the context of 3D printed structural beams, the selection and optimization of low-carbon cementitious composites are critical, not only to meet sustainability targets but also to ensure that fresh-state rheology and hardened-state mechanical properties align with the requirements of additive manufacturing. (Adelusi, *et al*., 2023, Ogunnowo, *et al*., 2023)

A primary category within low-carbon cementitious composites is the class of fly ash and slag-based geopolymers. These materials utilize industrial byproducts fly ash from coal combustion and ground granulated blast-furnace slag from steel production as aluminosilicate precursors. When activated with alkaline solutions such as sodium hydroxide and sodium silicate, these materials undergo a geopolymerization reaction, resulting in hardened binders that exhibit excellent chemical resistance, low permeability, and high early-age strength. Fly ash-rich mixes often provide superior workability and long open times, which are advantageous for layer-by-layer deposition in 3D printing (Adesemoye, *et al*., 2021, Ogeawuchi, *et al*., 2021). Slag-based formulations, on the other hand, offer greater compressive strength and durability. Together, these materials not only divert industrial waste from landfills but also reduce carbon emissions by eliminating the need for calcination and clinker production, processes responsible for a substantial share of cement's environmental impact (Adelusi, Ojika & Uzoka, 2022, Ogunnowo, *et al*., 2022). Figure 2 shows schematic sketch of the interlayer fibre reinforcement concept for 3DCP presented by Gebhard, *et al*., 2021.

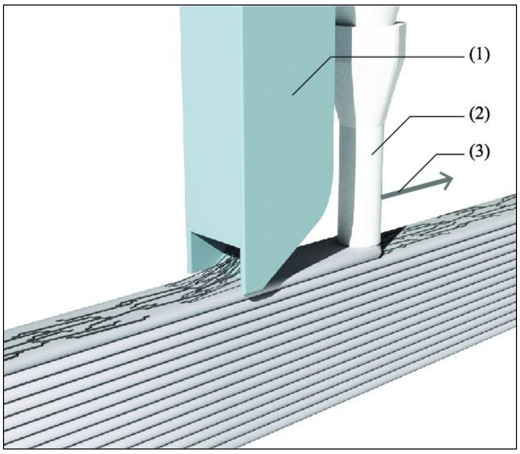

Fig 2: Schematic sketch of the interlayer fibre reinforcement concept for 3DCP (Gebhard, *et al*., 2021)

Limestone Calcined Clay Cement (LC^3) is another promising alternative in the low-carbon cementitious composite space. LC^3 is produced by blending clinker with limestone and calcined clay, typically in proportions that reduce the clinker factor by up to 50%. The synergy between calcined clay and limestone leads to the formation of additional calcium-alumino-silicate hydrates, enhancing both early and long-term strength (Adewoyin, *et al*., 2020, Nwani, *et al*., 2020). LC^3 offers better durability, reduced shrinkage, and improved resistance to aggressive environments, making it suitable for structural applications such as beams. In the context of 3D printing, LC^3's particle size distribution and hydration behavior can be optimized to yield a printable mix with controlled thixotropy and sufficient interlayer bonding. Its ability to achieve similar or superior strength to ordinary Portland cement (OPC) while lowering CO_2 emissions by up to 40% positions it as a highly effective binder for sustainable additive construction (Adewoyin, 2021, Ogunnowo, *et al*., 2021).

Recycled aggregate concrete blends represent another class of low-carbon materials being explored for 3D printing. These blends incorporate crushed concrete from demolition waste or recycled industrial materials such as glass, ceramic, or rubber as aggregate replacements. While recycled aggregates can impact workability and reduce early-age strength, proper mix design and the use of plasticizers or rheology modifiers can restore desired properties. In structural beams fabricated through 3D printing, the inclusion of recycled aggregates contributes to a circular economy, reducing landfill use and conserving natural resources (Adewoyin, 2021, Ojonugwa, *et al*., 2021). The challenge lies in ensuring consistency of quality and performance, especially since recycled aggregates may introduce variability in density, absorption, and residual contaminants.

For all low-carbon cementitious composites intended for 3D printing, achieving the appropriate rheological properties is fundamental. Rheology governs the flow behavior of the fresh mix, determining how easily it can be extruded through the nozzle and how well it retains its shape after deposition (Adewoyin, *et al*., 2020, Ogunnowo, *et al*., 2020). Critical rheological parameters include yield stress, plastic viscosity, and thixotropy. Yield stress must be high enough to support the weight of successive layers without collapse, but not so high as to prevent pumping or extrusion. Plastic viscosity should allow for smooth, continuous flow while minimizing the risk of segregation. Thixotropy, the time-dependent recovery of viscosity after shear, is particularly important in 3D printing, as it enables printed layers to regain stiffness quickly and maintain buildability (Okolo, *et al*., 2021, Oluoha, *et al*., 2021). Preinstall reinforcement and 3D concrete printing presented by Baduge, *et al*., 2021 is shown in figure 3.

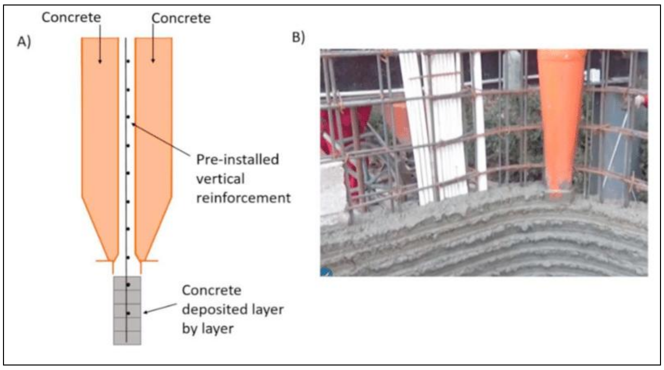

Fig 3: Preinstall reinforcement and 3D concrete printing (Baduge, *et al*., 2021)

To tailor these properties, mix designers utilize a range of additives such as viscosity modifying agents (VMAs), superplasticizers, accelerators, and retarders. For example, a fly ash-slag geopolymer might require additional silicate solution to enhance cohesion, while LC^3-based mixes may benefit from the inclusion of cellulose ethers or polycarboxylate ethers to manage water retention and reduce slump. Recycled aggregate blends often necessitate the use of supplementary fines or pozzolanic materials to improve packing density and reduce porosity. The ultimate goal is to create a mix that can be printed consistently, layer by layer, without cold joints or geometric distortion, while maintaining structural performance (Adewoyin, *et al*., 2020, Ogunnowo, *et al*., 2020).

Mechanical performance remains a central focus in the evaluation of low-carbon cementitious composites for 3D printed beams. Compressive strength, typically measured at 7, 28, and 56 days, is a key indicator of a material's ability to withstand axial loads and is directly influenced by binder chemistry, curing conditions, and mix proportions. Fly ash-slag geopolymers have demonstrated compressive strengths exceeding 50 MPa, with some formulations achieving early strength gains rivaling OPC. LC^3 systems typically attain compressive strengths in the range of 40–60 MPa, depending on the calcined clay content and particle fineness. Recycled aggregate blends show more variability but can achieve satisfactory strength through optimized gradation and the use of high-reactivity pozzolans (Adewoyin, *et al*., 2020, Olasoji, Iziduh & Adeyelu, 2020). Illustration of 3D printed beam and the direction of loading (red arrow) on the extracted cubes during the compression test presented by Srinivas, *et al*., 2022 is shown in figure 4.

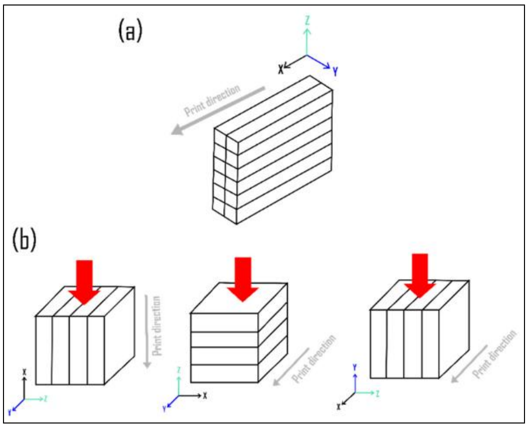

Fig 4: Illustration of 3D printed beam and the direction of loading (red arrow) on the extracted cubes during the compression test (Srinivas, *et al*., 2022)

Flexural strength, another critical parameter for structural beams, is often more sensitive to interfacial bonding and mix homogeneity. In 3D printed structures, anisotropy introduced by the layer-by-layer process can reduce flexural performance in directions perpendicular to the print path. This makes interlayer adhesion and curing strategy vital. Curing regimes such as steam curing or the application of curing membranes immediately after printing help prevent desiccation and enhance bond strength. Incorporating fiber reinforcements glass, basalt, or steel fibers can further enhance tensile and flexural performance, allowing the printed beam to withstand bending moments and reduce crack propagation (Adewoyin, *et al*., 2020, Olasoji, Iziduh & Adeyelu, 2020).

The environmental benefits of using low-carbon cementitious composites in 3D printed structural beams extend beyond carbon emission reductions. These materials support resource conservation by enabling the use of industrial waste, reducing dependency on virgin raw materials, and minimizing construction waste through precision printing. The additive manufacturing process itself enhances material efficiency by depositing only the required amount of material, avoiding the overuse common in conventional formwork-based methods. Furthermore, the ability to locally source materials such as fly ash, calcined clay, or recycled aggregates reduces transportation emissions and promotes regional supply chains (Adewoyin, *et al*., 2020, Olasoji, Iziduh & Adeyelu, 2020).

Lifecycle considerations further highlight the sustainability of these materials. Over a building's lifespan, low-carbon composites contribute to improved energy performance by providing thermal mass and potentially reducing heating and cooling loads. Their durability and resistance to chemical attack, particularly in the case of geopolymers, reduce maintenance needs and extend service life. At end-of-life, 3D printed components made from recyclable or demountable materials can be crushed and reused in future formulations, supporting a closed-loop material system. Environmental Product Declarations (EPDs) and Life Cycle Assessment (LCA) tools can help quantify these impacts, guiding designers and engineers toward more informed material choices (Adewoyin, *et al*., 2021, Ogunnowo, *et al*., 2021).

In conclusion, low-carbon cementitious composites offer a sustainable and technically viable pathway for the fabrication of 3D printed structural beams. Through careful material selection, rheological tuning, and performance optimization, these composites can meet the demanding requirements of structural integrity while significantly reducing environmental impact. Continued research into mix design, fiber reinforcement, interlayer adhesion, and lifecycle performance will be essential to advance the adoption of these materials in real-world infrastructure (Adewoyin, *et al*., 2021, Ogunnowo, *et al*., 2021). As additive manufacturing technologies evolve, low-carbon cementitious composites are poised to play a central role in redefining the way we build more efficiently, responsibly, and resiliently.

2.3 Additive Manufacturing of Structural Beams

Additive manufacturing, commonly referred to as 3D printing, has emerged as a transformative construction technology, particularly in the context of creating structural elements such as beams. In contrast to conventional methods that rely on formwork and manual labor, 3D printing offers an automated, layer-by-layer approach to fabricating components directly from digital models. When applied to structural beams using low-carbon cementitious composites, this process not only introduces opportunities for sustainable design but also poses unique technical challenges and demands new approaches to modeling performance. Understanding the implications of this technology for beam production involves examining the printing processes, material behavior, and structural performance under load (Adewoyin, *et al*., 2023, Oguejiofor, *et al*., 2023, Ubamadu, *et al*., 2023).

Several 3D printing technologies have been adapted for concrete and cementitious materials, with extrusion-based methods being the most widely used for structural applications. In extrusion-based printing, a pump feeds a fresh cementitious mix through a nozzle, depositing it layer by layer along a preprogrammed toolpath. The system may operate on a gantry-mounted platform or through robotic arms, enabling flexibility in geometry and build orientation. This technique is well-suited for producing beams, slabs, and wall elements, allowing customization of geometry and material distribution. It also enables design features that are difficult to achieve using traditional methods, such as variable cross-sections, embedded voids, or internal truss systems for weight reduction (Adewoyin, *et al*., 2021, Ogunnowo, *et al*., 2021).

The design of structural beams for additive manufacturing introduces both constraints and opportunities. On one hand, the absence of formwork eliminates the limitations imposed by molds, freeing designers to explore non-standard shapes, curvature, or integrated reinforcement pathways. On the other hand, the layered deposition process imposes practical constraints on overhang angles, minimum layer height, and cantilevered sections. The beam must be designed to be printable, meaning that each deposited layer must have sufficient support from the one below it, and the overall geometry must ensure stability during printing. Additionally, the mix must have appropriate buildability retaining its shape after deposition while still allowing for continuous flow during extrusion (Adanigbo, *et al*., 2024, Ojika, *et al*., 2024, Omotoye, *et al*., 2024).

One of the most critical challenges in the additive manufacturing of structural beams is achieving sufficient interlayer bonding. Since the beam is built incrementally, each layer must bond to the previously deposited one to act as a monolithic structural member. The degree of bonding is influenced by the time interval between layers, the moisture content, the rheology of the mix, and environmental conditions such as temperature and humidity. Inadequate bonding can lead to delamination, reduce flexural and shear strength, and introduce planes of weakness that compromise overall structural integrity. Print path strategies that minimize cold joints such as continuous printing without interruption or overlapping toolpaths can help improve bonding quality (Adeleke, 2021, Ojika, *et al*., 2021, Owobu, *et al*., 2021).

Anisotropy is another significant issue in 3D printed beams. Unlike cast elements, which are generally isotropic due to uniform compaction and curing, printed elements exhibit directional differences in mechanical properties. Typically, strength and stiffness are highest in the direction parallel to the layer deposition and weakest across layers. This anisotropy must be accounted for in structural modeling and design, particularly for beams subjected to bending, shear, or torsional loads. The print orientation relative to the principal stress directions becomes a critical factor in determining performance (Adeleke, 2024, Ojika, *et al*., 2024, Omaghomi, *et al*., 2024). Strategies to address anisotropy include optimizing the nozzle path, adjusting the layer thickness, and integrating reinforcement that spans across layers, such as steel bars, mesh, or fiber strands.

Buildability refers to the ability of the material and process to construct stable forms without collapse or deformation during printing. For structural beams, this means that the freshly printed lower layers must support the weight of the subsequent layers and any overlying features. The cementitious mix must exhibit early strength gain, dimensional stability, and resistance to flow under its own weight (Adewoyin, *et al*., 2024, Ohakawa, *et al*., 2024, Olu-lawal, *et al*., 2024, Umar, Okwandu & Akande, 2024). If the mix is too fluid, it may slump and distort the geometry; if it is too stiff, it may clog the nozzle or result in poor surface quality. Achieving the right balance involves careful tuning of the water-to-binder ratio, the use of accelerators or retarders, and the inclusion of viscosity-modifying agents to enhance thixotropic behavior (Adeleke, *et al*., 2024, Ogunsola, *et al*., 2024, Oyeyipo, *et al*., 2024). These additives allow the material to behave like a fluid during pumping and extrusion, yet stiffen rapidly after deposition to maintain shape.

Curing conditions play a pivotal role in the performance of 3D printed structural beams. Unlike traditional cast concrete, which benefits from enclosed formwork that retains moisture, printed elements are fully exposed to the environment from the moment they are deposited. This exposure increases the risk of surface drying, shrinkage cracking, and insufficient hydration, particularly in hot or dry conditions. Effective curing strategies are essential to ensure proper strength development and minimize differential shrinkage. These may include misting systems, curing blankets, or the application of curing compounds immediately after printing. In some cases, controlled environments or insulated enclosures are used during printing to manage temperature and humidity, though such solutions may increase complexity and cost (Adeleke, Igunma & Nwokediegwu, 2021, Osamika, *et al*., 2021).

Beam geometry and dimensions directly influence printability and performance. Slender beams with long spans present challenges in both printing and structural stability during and after the build process. Excessive deflection of fresh layers can result in geometric inaccuracy or misalignment of the toolpath. To mitigate these risks, temporary supports or built-in stiffening features may be included in the design. Alternatively, beams may be printed in segments and assembled post-printing using mechanical connectors, mortar joints, or adhesives. Segmental construction also facilitates transportation and installation on-site, especially for large beams that exceed the printer's build volume (Adeyemi, *et al*., 2024, Olatunde, Okwandu & Akande, 2024, Sodiya, *et al*., 2024).

Hollow sections and variable cross-sections are often explored in 3D printed beam design to reduce weight and material usage while maintaining strength. These features, while structurally efficient, require careful planning to avoid printing failures. For example, internal voids must be supported by bridging strategies or designed with self-supporting angles. Closed geometries can trap air or uncured material, leading to voids or defects unless adequately vented. Finite element modeling and computational fluid dynamics (CFD) simulations can be used to predict and optimize material behavior during printing, helping designers refine beam shapes and validate structural integrity before fabrication (Adeleke, Igunma & Nwokediegwu, 2022, Onasanya, Aroyewun & Okonkwo, 2022).

The integration of reinforcement into 3D printed beams remains an area of active research and development. While traditional concrete beams rely on steel reinforcement to resist tensile forces, embedding reinforcement in printed elements is more complex. Several approaches are being explored, including printing around pre-positioned rebar, incorporating continuous fiber reinforcement during deposition, or printing reinforcement with alternative materials such as carbon fiber composites. Each method has implications for structural performance, print speed, and system complexity. Ensuring bond strength between reinforcement and printed matrix is crucial, as slippage or poor anchorage can lead to premature failure (Adeleke, *et al*., 2024, Ojika, *et al*., 2024, Olu-lawal, *et al*., 2024).

In conclusion, additive manufacturing of structural beams using low-carbon cementitious composites introduces a new paradigm in sustainable construction. While the technology offers substantial benefits in terms of customization, material efficiency, and reduced formwork, it also presents technical challenges related to interlayer bonding, anisotropy, buildability, curing, and printability. Addressing these challenges requires a multidisciplinary approach involving material science, structural engineering, robotics, and digital design (Adeyemi, *et al*., 2024, Okwandu, *et al*., 2024, Osasona, *et al*., 2024, Ugwuanyi, *et al*., 2024). As research advances and practical experience accumulates, 3D printed structural beams are poised to become a viable, sustainable solution for modern infrastructure, reshaping the future of how we design and build load-bearing elements in the built environment.

2.4 Performance Modeling Techniques

Performance modeling techniques play a crucial role in advancing the design and application of 3D printed structural beams fabricated from low-carbon cementitious composites. These techniques enable engineers and researchers to predict how printed beams will respond to loads, optimize their material distribution for strength and efficiency, and guide the design process to meet safety and performance criteria. Given the unique characteristics of additive manufacturing such as anisotropy, layer-wise construction, and novel material formulations traditional modeling methods must be adapted or supplemented with advanced computational tools and iterative design strategies (Adeyemi, *et al*., 2024, Ojika, *et al*., 2024, Orenuga, *et al*., 2024, Ubamadu, *et al*., 2024). This comprehensive approach ensures that structural beams not only meet their functional requirements but also leverage the sustainability benefits of low-carbon composites.

Finite Element Analysis (FEA) is among the most widely used computational methods for predicting the structural response of 3D printed beams. FEA divides the beam's geometry into a mesh of discrete elements, within which the equations governing stress, strain, and displacement are solved under specified boundary conditions and loading scenarios. For beams printed with low-carbon cementitious composites, FEA models must incorporate material anisotropy resulting from the layer-by-layer deposition process. This anisotropy often manifests as weaker bonding between printed layers, which affects tensile and shear strength differently along various axes (Adeleke, *et al*., 2024, Olatunde, *et al*., 2024, Osamika, *et al*., 2024). Accurate material models within FEA therefore include directional elastic moduli, fracture toughness, and plasticity parameters calibrated from experimental data.

FEA enables simulation of multiple load cases, including bending moments, axial loads, shear forces, and combined stresses. It also allows for the evaluation of displacement, stress concentrations, and potential failure points. These insights are vital for identifying critical sections of the beam that require reinforcement or geometric modification. Additionally, FEA supports the analysis of complex beam geometries, including curved, tapered, or hollow sections, which are common in 3D printed components due to the design freedom enabled by additive manufacturing. Dynamic loading scenarios, such as vibration or impact, can also be simulated to assess the beam's performance under real-world conditions (Adeleke, *et al*., 2024, Ogunsola, *et al*., 2024, Oriekhoe, *et al*., 2024).

Topology optimization complements FEA by guiding the efficient distribution of material within the beam's volume. This computational technique uses iterative algorithms to remove or redistribute material in regions experiencing low stress, thereby reducing weight without compromising structural integrity. In the context of low-carbon cementitious composites, topology optimization is particularly valuable as it maximizes the use of sustainable materials, minimizing waste and embodied carbon (Adeleke, *et al*., 2024, Okwandu, *et al*., 2024, Olatunde, *et al*., 2024). The resulting optimized geometries often feature intricate internal lattices, variable thicknesses, and hollow cores that traditional manufacturing methods cannot economically produce but are readily fabricated through 3D printing.

Topology optimization frameworks integrate directly with FEA models by setting objective functions such as minimizing compliance (maximizing stiffness) or reducing mass subject to constraints like maximum allowable stress or displacement. Advanced optimization algorithms employ gradient-based methods or evolutionary strategies to explore large design spaces efficiently. These methods allow designers to balance competing demands, for example, ensuring that lightweight beams still meet safety factors while optimizing print time and material use. The optimized designs also accommodate the unique anisotropic behavior of printed composites, adjusting internal structures to mitigate weaknesses between layers (Onaghinor, Uzozie & Esan, 2021).

Parametric and generative design methods offer a flexible and performance-driven approach to modeling 3D printed beams. Parametric design uses variables and parameters to control geometry and material properties, allowing quick exploration of design variants by adjusting inputs such as beam length, cross-sectional shape, infill density, or fiber orientation. This enables iterative optimization and customization tailored to specific project requirements or site conditions. Parametric models are often linked with simulation tools, creating feedback loops where performance results inform subsequent design adjustments (Adeyemi, *et al*., 2024, Okonkwo, 2024, Olatunde, *et al*., 2024, Sodiya, *et al*., 2024).

Generative design extends this concept by employing algorithms that automatically generate design options based on predefined performance goals and constraints. Using techniques from artificial intelligence and computational geometry, generative design tools can propose novel beam shapes, internal lattice configurations, and reinforcement patterns that human designers might not conceive. These designs optimize for multiple objectives simultaneously such as structural performance, material efficiency, and manufacturability resulting in innovative forms that push the boundaries of traditional structural engineering (Okwandu, *et al*., 2024, Olajiga, *et al*., 2024, Oriekhoe, *et al*., 2024, Umar, Okwandu & Akande, 2024).

The integration of parametric and generative design with additive manufacturing creates a seamless design-to-fabrication workflow. Designers start with performance goals, generate a variety of beam models, and simulate their responses through FEA or other analysis tools. The most promising models can be refined further before being converted into machine-readable toolpaths for 3D printing. This approach accelerates the development cycle, reduces reliance on physical prototyping, and increases confidence in the final printed product (Onaghinor, Uzozie & Esan, 2021).

Validation of computational performance models is essential to ensure their accuracy and reliability. Physical experiments involving mechanical testing of printed beam specimens provide empirical data to calibrate and verify simulation parameters. Tests typically include compressive strength, flexural strength, tensile strength, and fracture toughness under controlled loading conditions. Specimens may be printed with various orientations, layer heights, and material compositions to evaluate anisotropy effects and interlayer bonding quality (Adeyemi, *et al*., 2024, Ogunnowo, *et al*., 2024, Osho, *et al*., 2024, Ubamadu, *et al*., 2024).

Benchmarks from standard testing protocols, such as ASTM or ISO standards adapted for additive manufacturing, offer a comparative basis for model validation. Digital models are iteratively refined to align with experimental outcomes, adjusting material properties, boundary conditions, or failure criteria as needed. Such validation is crucial because printed cementitious composites can exhibit non-linear and time-dependent behavior due to factors like curing dynamics, moisture content, and microstructural variations (Adeyemi, *et al*., 2024, Ogunbiyi-Badaru, *et al*., 2024, Oyeyemi, *et al*., 2024, Umoh, *et al*., 2024).

Some studies employ advanced characterization techniques such as digital image correlation (DIC) to map strain distributions on specimen surfaces, providing detailed insight into deformation and crack propagation. Microstructural analysis using scanning electron microscopy (SEM) or X-ray computed tomography (CT) complements mechanical testing by revealing porosity, fiber distribution, and layer interfaces. This comprehensive dataset enriches the performance modeling framework, enabling more predictive and robust design tools.

In addition to laboratory validation, in-situ monitoring during printing and early-stage loading tests on full-scale beams help assess real-world behavior. Sensor technologies embedded in printed beams can measure strain, temperature, and displacement in real-time, providing continuous feedback on structural health and integrity. This data can be integrated into performance models to update predictions and support maintenance planning.

In conclusion, performance modeling techniques for 3D printed structural beams using low-carbon cementitious composites encompass a suite of computational and experimental approaches that address the unique challenges posed by additive manufacturing. Finite Element Analysis provides detailed structural response predictions essential for safe and efficient design. Topology optimization drives material efficiency and innovation in beam geometry. Parametric and generative design enable rapid exploration of performance-driven solutions. Rigorous validation through physical experiments and benchmarks ensures that models reflect real material behavior and loading conditions (Adeyemi, *et al*., 2024, Ogeawuchi, *et al*., 2024, Osasona, *et al*., 2024, Ugwuanyi, *et al*., 2024). Together, these techniques form the backbone of a design framework that not only advances sustainable construction but also unlocks the full potential of 3D printing in modern infrastructure development.

2.5 AI and Machine Learning in Structural Performance Prediction

Artificial intelligence (AI) and machine learning (ML) techniques are rapidly transforming structural performance prediction, offering new capabilities to analyze complex behaviors of 3D printed structural beams fabricated from low-carbon cementitious composites. Traditional computational methods such as finite element analysis (FEA) provide detailed insights but can be computationally intensive and require precise material models that may be difficult to obtain for novel additive manufacturing materials (Afolabi, *et al*., 2020, Nwani, *et al*., 2020). AI and ML offer data-driven alternatives or complements that can efficiently capture nonlinear relationships between inputs and structural responses, accelerating design cycles and enhancing predictive accuracy. The application of various AI/ML algorithms including Artificial Neural Networks (ANN), Support Vector Machines (SVM), Random Forest, and Gradient Boosting Models has opened new frontiers in performance modeling for additive manufacturing with sustainable materials.

Artificial Neural Networks (ANN) are among the most popular AI models for structural prediction due to their ability to approximate complex nonlinear functions. Inspired by the human brain's architecture, ANNs consist of interconnected nodes (neurons) organized in layers that process input data and generate outputs. In the context of 3D printed beams, ANNs can be trained to predict structural properties such as compressive strength, flexural strength, or deflection based on a range of inputs including mix design parameters, printing process variables, geometric characteristics, and loading conditions (Onaghinor, Uzozie & Esan, 2021). Due to their flexibility, ANNs can model anisotropic behavior resulting from layer-wise deposition and interlayer bonding, capturing subtle dependencies that are challenging to represent in traditional analytical models. However, ANNs require large datasets for effective training and are sometimes criticized for their "black-box" nature, meaning their internal decision-making process is not easily interpretable.

Support Vector Machines (SVM) offer an alternative supervised learning method for regression and classification tasks in structural modeling. SVMs work by finding the optimal hyperplane that separates data points in high-dimensional feature space, enabling robust predictions even with limited training data (Afolabi, *et al*., 2022, Ogunnowo, *et al*., 2022). In predicting beam performance, SVMs have been used to classify failure modes or estimate strength parameters based on input features such as printing orientation, layer thickness, and curing regime. SVMs are known for their ability to generalize well and avoid overfitting, making them suitable for applications where dataset size or quality may be constrained. However, they are less flexible than ANNs in capturing highly nonlinear behavior unless kernel functions are carefully selected and tuned (Ozobu, 2020).

Ensemble methods such as Random Forest and Gradient Boosting Models provide another powerful approach to structural performance prediction. Random Forest algorithms build multiple decision trees on subsets of data and aggregate their outputs to improve accuracy and reduce variance. Gradient Boosting iteratively trains weak learners, combining them into a strong predictive model by minimizing errors. These methods excel in handling heterogeneous data and complex interactions among input variables (Afolabi, *et al*., 2020, Ozobu, 2020). For 3D printed cementitious beams, Random Forests can identify the relative importance of material properties, geometric features, and process parameters in influencing strength and stiffness, offering interpretable insights into design sensitivities. Gradient Boosting has been employed to enhance regression accuracy for predicting deflection and crack propagation patterns under various loading scenarios. These ensemble techniques often require less data preprocessing and exhibit robustness against noise in experimental measurements.

The quality and comprehensiveness of datasets used for training AI/ML models are fundamental to their success. Input data typically encompass material properties such as compressive strength, modulus of elasticity, and fracture toughness, which may vary based on mix composition and curing conditions. Geometric parameters include beam dimensions, cross-sectional shape, and internal infill patterns, which influence load distribution and stiffness. Loading conditions such as point loads, uniformly distributed loads, and cyclic or dynamic loads complete the set of inputs defining the structural problem (Ozobu, 2020). Additional factors such as print orientation, layer height, interlayer time intervals, and environmental conditions (temperature, humidity) can further refine model accuracy by capturing the complex dependencies introduced by additive manufacturing.

Obtaining high-quality datasets often involves a combination of laboratory experiments, in-situ measurements, and synthetic data generated from physics-based simulations. Experimental campaigns may test printed beam specimens under standardized loading to record ultimate strength, elastic modulus, and failure modes. Simulations augment this data by exploring parameter spaces not easily accessible experimentally, generating large volumes of labeled data for supervised learning (Samuel & David, 2019). Data augmentation techniques, including noise injection or interpolation between known data points, help improve model generalization. Ensuring diversity and representativeness in training data is critical to avoid bias and overfitting, especially given the variability inherent in recycled or low-carbon cementitious composites.

Model accuracy, training time, and computational efficiency are important considerations when selecting and deploying AI/ML techniques for structural beam prediction. ANNs, particularly deep learning architectures with multiple hidden layers, can achieve high accuracy but often require extensive training time and computational resources. Their performance depends heavily on hyperparameter tuning, network architecture design, and availability of large training datasets. SVMs typically train faster and require fewer data but may struggle with complex nonlinearities without appropriate kernel selection. Ensemble methods like Random Forest and Gradient Boosting strike a balance, offering robust predictions with moderate computational demand and greater interpretability (Ozobu, 2020, Sobowale, *et al*., 2020).

Trade-offs exist between model complexity and usability. Highly complex models may offer marginal gains in accuracy but become impractical for routine design applications due to their training overhead and interpretability issues. Simpler models or surrogate models that approximate detailed physics simulations can provide fast, approximate predictions for early-stage design exploration. In practice, a tiered approach combining rapid low-fidelity models with targeted high-fidelity simulations can optimize the design workflow. Model interpretability is especially important in engineering contexts to build trust among practitioners and support decision-making under uncertainty (Adeleke, *et al*., 2024, Ogunnowo, *et al*., 2024, Oyeyemi, Orenuga & Adelakun, 2024).

Hybrid modeling approaches that integrate physics-informed machine learning (PIML) represent a promising frontier in structural performance prediction. PIML incorporates known physical laws such as conservation of mass, momentum, and energy as constraints or priors within machine learning frameworks. This approach reduces reliance on purely data-driven correlations, improving extrapolation capabilities and ensuring consistency with fundamental mechanics. For 3D printed beams, physics-informed models can encode constitutive behavior of cementitious composites, anisotropic elasticity, and fracture mechanics, guiding the ML algorithms to physically plausible solutions even in data-sparse regimes (Adeleke, *et al*., 2024, Ogunbiyi-Badaru, *et al*., 2024, Santos, Okwandu & Akande, 2024). Such hybrid models also facilitate transfer learning, where knowledge from one domain (e.g., traditional concrete beams) can inform predictions in new material contexts like low-carbon printed composites.

By combining empirical data, computational mechanics, and AI, PIML enables more reliable and generalizable performance modeling. This integration supports uncertainty quantification and sensitivity analysis, providing designers with confidence intervals and risk assessments. Furthermore, physics-informed approaches can incorporate multi-scale modeling, linking microstructural features such as pore structure and fiber distribution to macro-scale beam behavior. This holistic perspective is essential to optimize material formulations and printing parameters concurrently with structural design (Adeleke, *et al*., 2024, Ogundipe, *et al*., 2024, Omaghomi, *et al*., 2024).

In conclusion, AI and machine learning techniques offer transformative potential for the performance modeling of 3D printed structural beams using low-carbon cementitious composites. Artificial Neural Networks, Support Vector Machines, and ensemble methods provide diverse tools to capture complex nonlinear relationships among material properties, geometry, and loading conditions (Afolabi, *et al*., 2022, Ojika, *et al*., 2022). The quality and scope of datasets, along with computational considerations, guide model selection and deployment. Hybrid physics-informed ML models represent a cutting-edge approach that integrates fundamental mechanics with data-driven learning, enhancing prediction accuracy and robustness (Afolabi, *et al*., 2020, Ogunnowo, *et al*., 2020). As additive manufacturing technologies continue to evolve, these AI-driven modeling techniques will be instrumental in optimizing sustainable, high-performance structural components and accelerating their adoption in modern infrastructure.

2.6 Case Studies and Practical Applications

The field of 3D printed structural beams using low-carbon cementitious composites is rapidly evolving, with an increasing number of experimental and simulation-based studies shedding light on the material behavior, design optimization, and performance prediction of these innovative structural elements (Afolabi, *et al*., 2022, Ojika, *et al*., 2022, Owobu, *et al*., 2022). The integration of low-carbon materials with additive manufacturing technologies offers a promising pathway toward sustainable and customizable infrastructure components, but practical adoption hinges on robust performance modeling validated by empirical evidence. A review of published case studies and practical applications provides valuable insights into current capabilities, challenges, and future directions (Afolabi, *et al*., 2021, Okonkwo & Onasanya, 2021).

Experimental investigations form the backbone of understanding the mechanical behavior of 3D printed beams fabricated from low-carbon cementitious composites. Numerous studies have explored the compressive, flexural, and tensile properties of beams printed with geopolymer mixes, limestone calcined clay cement (LC^3), and recycled aggregate concrete blends. For instance, researchers have printed beams with fly ash-slag based geopolymers and subjected them to three-point bending tests to evaluate flexural strength and crack propagation patterns. These experimental setups often include beams printed in different orientations to assess anisotropy arising from the layer-by-layer deposition process (Adeleke & Peter, 2021, Ojonugwa, *et al*., 2021, Onoja, *et al*., 2021). The results frequently reveal reduced strength and stiffness in directions perpendicular to the print layers, highlighting the importance of interlayer bonding in structural integrity.

Simulation-based studies complement experimental work by enabling detailed exploration of design variables, boundary conditions, and load cases that are difficult to test physically due to time, cost, or scale constraints. Finite Element Analysis (FEA) models calibrated with experimental data have been used to predict the performance of 3D printed beams with varying cross-sectional geometries, reinforcement strategies, and material compositions. Some studies employ parametric models linked with topology optimization algorithms to identify efficient material distributions that maximize strength while minimizing weight and material use (Olurin, *et al*., 2023, Omisola, *et al*., 2023, Oyeyemi, 2023). The combination of simulation and physical testing facilitates iterative refinement of both mix design and beam geometry, leading to improved printability and performance.

Comparative analysis across different beam types, materials, and modeling approaches reveals notable trends and trade-offs. Beams fabricated from geopolymer composites often demonstrate higher early strength and better durability compared to those made with recycled aggregate concretes, which may suffer from variability in aggregate quality and weaker matrix-aggregate bonding (Afolabi, *et al*., 2021, Onoja, *et al*., 2021, Owobu, *et al*., 2021). LC^3-based beams offer a balanced compromise with moderate strength gains and significantly reduced carbon footprint relative to ordinary Portland cement concrete. In terms of geometry, solid rectangular beams provide baseline performance data, but the exploration of hollow or lattice-structured beams fabricated via 3D printing indicates substantial potential for reducing weight without compromising load capacity. These complex geometries pose additional modeling challenges, requiring advanced meshing techniques and material property assumptions to accurately capture stress distributions (Olurin, *et al*., 2023, Osamika, *et al*., 2023).

Modeling approaches vary from classical linear elastic FEA to nonlinear fracture mechanics and coupled multiphysics simulations that account for moisture transport and curing kinetics. While simpler models offer quick assessments, their accuracy is limited by assumptions of isotropy and uniform material properties. More sophisticated models incorporating anisotropic elasticity and cohesive zone models for crack propagation achieve better alignment with experimental outcomes but demand greater computational resources and detailed input data (Adelusi, Ojika & Uzoka, 2022, Ojika, *et al*., 2022, Oyeyemi, 2022). Hybrid approaches that integrate machine learning algorithms with physics-based simulations have shown promise in improving prediction accuracy while reducing computational costs, particularly in capturing the effects of print parameters and curing conditions on mechanical performance.

Several lessons emerge from these case studies that are highly relevant to industry practitioners and researchers aiming to deploy 3D printed structural beams in real-world applications. First, material consistency and quality control remain critical. Variations in mix composition, printing parameters, and environmental conditions can significantly influence beam performance, underscoring the need for standardized protocols in material preparation and printing. Second, interlayer bonding quality is a persistent challenge that directly impacts structural integrity, especially in load-bearing applications (Adelusi, Ojika & Uzoka, 2022, Onasanya, Aroyewun & Okonkwo, 2022). Strategies such as optimizing print speed, nozzle height, and layer curing time have been effective in enhancing bond strength. Incorporating fibers or other reinforcements within the mix or as embedded elements during printing further improves tensile and flexural performance.

Third, design flexibility afforded by 3D printing demands sophisticated modeling tools that can accommodate complex geometries and anisotropic material behavior. The integration of parametric design with simulation enables tailored beam solutions that meet specific structural and sustainability criteria. Fourth, real-time monitoring and adaptive control during printing improve build quality by detecting defects and adjusting process parameters, but these technologies are still in early stages of industrial adoption (Adelusi, Ojika & Uzoka, 2022, Onibokun, *et al*., 2023).

Industry-relevant outcomes from these studies include demonstrable reductions in material waste and carbon emissions compared to traditional beam fabrication methods. The ability to fabricate complex, optimized geometries leads to more efficient use of materials and improved structural performance. Some pilot projects have successfully implemented 3D printed beams in non-critical structural applications such as secondary framing or architectural features, paving the way for broader acceptance as confidence in modeling and testing methodologies grows (Adelusi, Ojika & Uzoka, 2022, Onasanya, Aroyewun & Okonkwo, 2022).

In summary, the growing body of experimental and simulation research on 3D printed structural beams using low-carbon cementitious composites highlights the significant potential and current limitations of this emerging technology. Comparative analyses provide a nuanced understanding of how material choice, beam geometry, and modeling techniques influence performance, while lessons learned inform best practices in design and fabrication (Afolabi, *et al*., 2021, Okwandu & Chukudi, 2021). Continued interdisciplinary collaboration, enhanced material characterization, and refinement of predictive models will be essential to translate these promising case studies into scalable, industry-ready solutions that contribute to sustainable infrastructure development.

2.7 Challenges and Future Research Directions

The performance modeling of 3D printed structural beams using low-carbon cementitious composites represents a promising frontier in sustainable construction technology. However, despite significant advances, several challenges persist that hinder the transition from laboratory-scale research to widespread industrial application. Addressing these challenges is essential to fully realize the benefits of additive manufacturing combined with environmentally friendly materials. Furthermore, future research directions must focus on integrating emerging technologies such as real-time structural health monitoring, standardization protocols, and digital twin frameworks to optimize design and ensure reliability at scale (Afolabi, *et al*., 2021, Ojika, *et al*., 2021).

One of the foremost challenges lies in scaling up 3D printing technologies for large-scale structural applications. While small-scale prototypes and beam specimens have demonstrated promising mechanical properties and printability, the translation to full-scale beams suitable for real infrastructure projects remains complex. Scaling introduces a range of technical difficulties, including maintaining print accuracy over long spans, ensuring consistent material properties throughout large volumes, and managing the cumulative effects of anisotropy and interlayer bonding over extended layers (Adelusi, Ojika & Uzoka, 2023, Ojika, *et al*., 2023). Variability in ambient conditions such as temperature and humidity becomes more pronounced, potentially affecting curing kinetics and layer adhesion. Equipment limitations such as nozzle size, pumping capacity, and robotic arm reach also constrain the feasible dimensions and geometries of printed beams.

Performance models developed at small scales may not directly extrapolate to large structures due to nonlinear scaling effects and the increased likelihood of defects or inhomogeneities. Thus, new modeling approaches are required that incorporate scale-dependent factors and probabilistic failure mechanisms (Afolabi, *et al*., 2022, Okonkwo, *et al*., 2022). Coupled multi-physics simulations that integrate mechanical, thermal, and chemical curing processes could provide deeper insights but demand substantial computational resources. Additionally, practical challenges in logistics and on-site printing such as material delivery, print speed, and environmental control must be integrated into performance predictions to ensure feasibility (Adelusi, Ojika & Uzoka, 2024, Ogunnowo, *et al*., 2024, Sikhakhane-Nwokediegwu, *et al*., 2024). Research must therefore focus on developing scalable modeling frameworks validated by full-scale experimental data, possibly through pilot construction projects.

Integrating real-time structural health monitoring (SHM) into 3D printed beams offers a transformative opportunity to enhance safety, durability, and lifecycle management. SHM systems employ embedded or surface-mounted sensors to continuously track strain, displacement, temperature, humidity, and other critical parameters during the service life of the beam. When combined with performance models, these data streams enable predictive maintenance, early detection of damage, and adaptive load management (Afolabi, *et al*., 2021, Ogunnowo, *et al*., 2021). However, embedding sensors in printed low-carbon cementitious beams introduces new challenges, including ensuring sensor durability during printing and curing, maintaining signal integrity through heterogeneous composite materials, and managing power and data transmission in built environments (Adelusi, *et al*., 2020, Ojika, *et al*., 2020).

Modeling frameworks need to evolve to assimilate real-time SHM data, enabling dynamic updating of structural state and recalibration of predictive models. This requires advanced data fusion techniques, machine learning algorithms for anomaly detection, and cloud-based platforms for remote monitoring. The integration of SHM with 3D printed beams also opens pathways for smart infrastructure that can self-assess and respond to environmental or loading changes. Future research must address the optimization of sensor placement, the development of robust sensor materials compatible with cementitious composites, and the creation of standardized protocols for SHM-enabled performance modelling (Adelusi, *et al*., 2022, Ojika, *et al*., 2022, Otokiti, *et al*., 2022).

Standardization in printable low-carbon beam design is critical to move additive manufacturing from experimental stages to regulated industry practice. Currently, the absence of unified guidelines and codes hinders regulatory approval, quality assurance, and market adoption. Variations in material formulations, printing parameters, and beam geometries create a fragmented landscape where performance claims are difficult to verify and compare. Without standardized test methods, material classifications, and design criteria tailored to 3D printed low-carbon composites, engineers face uncertainty in specifying components for structural applications (Adelusi, *et al*., 2023, Onibokun, *et al*., 2023).

Developing comprehensive standards involves collaboration among researchers, industry stakeholders, regulatory bodies, and standard organizations. These standards should define minimum mechanical properties, durability requirements, fire resistance, and safety factors specific to printed beams. They should also establish protocols for printing process control, quality monitoring, and post-print inspection. Performance modeling techniques must be harmonized with these standards, providing validated tools for design verification and certification. The establishment of open-access databases compiling material properties, printing parameters, and failure modes will support benchmarking and continuous improvement (Adelusi, *et al*., 2024, Ogunbiyi-Badaru, *et al*., 2024, Oyeyemi, *et al*., 2024). Future research should focus on creating universally accepted frameworks that accommodate the unique aspects of additive manufacturing while aligning with existing structural design codes.

The concept of digital twins represents a frontier with immense potential for revolutionizing the design and management of 3D printed structural beams. Digital twins are virtual replicas of physical structures that mirror their geometry, material state, and environmental interactions in real time. Coupling digital twins with performance models and SHM data allows for continuous, automated optimization of beam design, fabrication, and maintenance. This integration facilitates predictive analytics, enabling stakeholders to anticipate failure, optimize load distribution, and adapt structural configurations dynamically (Ojika, *et al*., 2022, Osamika, *et al*., 2022).

For 3D printed low-carbon beams, digital twins can simulate not only structural behavior but also curing processes, moisture diffusion, and chemical changes, providing a holistic view of performance throughout the beam's lifecycle. Automated design optimization algorithms embedded within the digital twin framework can explore a vast design space, balancing competing objectives such as strength, sustainability, cost, and printability. These algorithms can incorporate feedback from actual print outcomes and service data, refining the beam's design iteratively and supporting mass customization without compromising quality (Adelusi, *et al*., 2023, Ojika, *et al*., 2023, Uwaoma, *et al*., 2023).

Realizing the full potential of digital twins requires advances in multi-scale modeling, high-fidelity sensor integration, cloud computing infrastructure, and user-friendly visualization tools. Research must address challenges in data interoperability, model updating frequency, and cybersecurity. The adoption of digital twins in construction also depends on developing standards for data exchange and model validation to ensure trustworthiness and regulatory compliance. Despite these hurdles, the convergence of additive manufacturing, low-carbon composites, and digital twin technology promises a paradigm shift toward intelligent, resilient, and sustainable infrastructure (Adelusi, *et al*., 2023, Okogwu, *et al*., 2023, Ubamadu, *et al*., 2023).

In summary, the challenges facing performance modeling of 3D printed structural beams using low-carbon cementitious composites encompass scalability, real-time monitoring integration, standardization, and digital innovation. Overcoming these obstacles requires multidisciplinary research that bridges materials science, structural engineering, data science, and manufacturing technology (Adelusi, *et al*., 2023, Ojo, *et al*., 2023, Stephen, 2023). Future work must develop scalable models validated by large-scale experiments, embed structural health monitoring to enable adaptive management, establish comprehensive design and testing standards, and leverage digital twins for continuous optimization. Addressing these areas will pave the way for the reliable, efficient, and sustainable deployment of additive manufacturing in structural beam production, fundamentally transforming modern construction toward a more eco-conscious and technologically advanced future (Adelusi, *et al*., 2023, Oke, *et al*., 2023, Ozobu, *et al*., 2023).

2.8 Conclusion

Performance modeling of 3D printed structural beams using low-carbon cementitious composites represents a vital intersection of sustainable material science, digital fabrication, and structural engineering. The findings underscore that with appropriate modeling techniques ranging from finite element analysis and topology optimization to advanced machine learning frameworks accurate predictions of mechanical behavior and failure modes can be achieved despite the unique challenges posed by additive manufacturing processes. These models enable optimization of material use, improved structural safety, and tailored design flexibility, which are essential for the broader adoption of 3D printed low-carbon beams in modern infrastructure.

This body of research contributes significantly to sustainable structural engineering by facilitating the use of environmentally friendly composites that reduce embodied carbon without sacrificing performance. It also advances digital construction methods by integrating computational design, simulation, and manufacturing workflows, thus enabling more efficient, customizable, and resource-conscious building practices. By bridging empirical data with predictive analytics, performance modeling supports not only innovation in materials and geometries but also rigorous validation necessary for regulatory acceptance and real-world implementation.

Looking forward, the integration of real-time monitoring, digital twins, and physics-informed machine learning promises to further enhance the fidelity and applicability of performance models. These developments align closely with global net-zero goals by promoting designs that minimize waste, optimize resource use, and extend service life. As performance modeling techniques evolve, they will play an increasingly central role in enabling additive manufacturing to deliver structurally sound, sustainable, and adaptable building components, fundamentally transforming how we conceive, design, and construct the built environment for a resilient and low-carbon future.

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