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Smart Materials and Digital Twins: Synergistic Applications for Carbon Neutrality in Urban Infrastructure

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ABSTRACT

With urban infrastructure accounting for over 40% of global lifecycle carbon emissions, carbon neutrality in this sector has become a core global climate goal. The integration of smart materials (SMs) and digital twin (DT) technology shows great potential for carbon mitigation by optimizing resource use, boosting energy efficiency and advancing circular economy, though existing research lacks systematic exploration of its full-lifecycle application for carbon neutrality. This study fills the gap by establishing a carbon-neutral oriented SM-DT integration framework: clarifying emission reduction mechanisms of typical SMs, building a DT-based carbon monitoring and optimization system, proposing targeted integration paths for key infrastructure types, verifying effects via cross-continental cases, and offering implementation strategies. It provides a carbon-centric theoretical framework and practical guidance for stakeholders.

Keywords: Smart materials; Digital twin; Urban infrastructure; Carbon neutrality; Lifecycle carbon emission; Circular economy

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1. Introduction

1.1 Research Background and Significance

The global commitment to achieving the 1.5°C temperature control target under the Paris Agreement has pushed carbon neutrality to the top of the policy agenda in most countries (IPCC, 2023). Urban infrastructure, as the backbone of urban develop ment, covers transportation, buildings, and municipal utilities, and its lifecycle carbon emissions (including embodied carbon from construction and operational carbon from use) account for 40-50% of global total carbon emissions (UNEP, 2024). Traditional infrastructure management faces significant challenges in carbon emission control: the construction phase relies on high-carbon materials such as cement and steel, the operation phase suffers from inefficient energy use due to lack of real-time monitoring, and the deconstruction phase generates massive construction waste with low recycling rates (European Commission, 2025). To address these issues, innovative technologies are urgently needed to transform infrastructure from high-carbon to low-carbon operation.

Smart materials, with their unique functional properties such as energy harvesting, self-healing, and adaptive regulation, can directly reduce carbon emissions by reducing material consumption and energy use (Li et al., 2025). For example, piezoelectric materials can convert vibration energy into electrical energy, reducing reliance on fossil energy; self-healing concrete can extend infrastructure service life, reducing the carbon emissions associated with reconstruction (Chen et al., 2025). Digital twin technology, which realizes real-time mapping and lifecycle simulation between physical and virtual entities, provides a precise platform for tracking, monitoring, and optimizing carbon emissions across the entire lifecycle (Rodriguez et al., 2024). The integration of SMs and DTs forms a „sensing-optimization-action" closed loop: SMs collect real-time carbon-related data (e.g., material carbon footprint, energy consumption), while DTs analyze and optimize carbon emission reduction strategies, enabling targeted carbon mitigation in each lifecycle stage. This synergistic effect makes SM-DT integration a key technical path to achieve infrastructure carbon neutrality.

However, existing studies on SM-DT integration mainly focus on resilience enhancement and lifecycle cost optimization, with insufficient attention to carbon neutrality as the core goal. There is a lack of systematic research on how to match smart materials with digital twin functions to achieve lifecycle carbon emission reduction, and no unified application framework has been formed to guide practical implementation. Therefore, exploring the synergistic application of SM-DT integration for infrastructure carbon neutrality has important theoretical value and practical significance for promoting global climate action and sustainable urban development.

1.2 Research Objectives and Scope

This study aims to establish a carbon-neutral oriented application framework for SM-DT integration in urban infrastructure and verify its effectiveness through case studies. The specific research objectives are: (1) to clarify the carbon emission reduction mechanisms of typical smart materials in infrastructure lifecycle; (2) to construct a digital twin-based lifecycle carbon emission monitoring and optimization system; (3) to propose targeted SM-DT integration paths for different infrastructure types to achieve stage-specific carbon reduction goals; (4) to evaluate the carbon emission reduction effects of the integrated technology through cross-regional case studies; (5) to identify key barriers to implementation and propose policy and technical strategies. The research scope covers three key urban infrastructure types: transportation infrastructure (highways, bridges), building infrastructure (commercial buildings, public hospitals), and municipal utility infrastructure (sewage treatment plants, gas supply networks). The smart materials involved include piezoelectric energy-harvesting materials, self-healing concrete, phase change materials (PCMs), and low-carbon recyclable composites; the digital twin technology focuses on carbon emission simulation, real-time monitoring, and strategy optimization.

1.3 Research Methodology

This study adopts a mixed research method combining systematic literature review, framework construction, case study analysis, and quantitative evaluation. First, a systematic search was conducted in academic databases (Web of Science, Scopus, ScienceDirect) using keywords such as „smart materials“, „digital twin“, „urban infrastructure“, „carbon neutrality“, and „lifecycle carbon emission“. The literature was restricted to studies published between 2022 and 2025 to ensure timeliness, resulting in 320 initial retrievals and 168 in-depth analyzed studies after screening. Second, based on the literature review, the carbon emission reduction mechanisms of smart materials were clarified, and a carbon-neutral oriented SM-DT integration framework was constructed. Third, 6 representative cross-regional case studies were selected, covering different infrastructure types and lifecycle stages, and the carbon emission reduction effects were evaluated using indicators such as embodied carbon reduction rate, operational carbon reduction rate, and lifecycle carbon emission reduction efficiency. Finally, the key barriers to implementation were identified through expert interviews and literature analysis, and targeted strategies were proposed.

1.4 Structure of the Paper

The remainder of this paper is structured as follows: Section 2 elaborates on the theoretical basis of infrastructure carbon neutrality and the carbon emission reduction mechanisms of SM-DT integration. Section 3 constructs the carbon-neutral oriented SM-DT integration framework and analyzes the key components. Section 4 proposes targeted integration paths for typical urban infrastructure types. Section 5 presents and discusses cross-regional case studies. Section 6 identifies key barriers to promoting SM-DT integration for carbon neutrality. Section 7 proposes policy and technical strategies. Section 8 summarizes the main conclusions and future research directions.

2. Theoretical Basis: Infrastructure Carbon Neutrality and SM-DT Synergy

2.1 Connotation and Evaluation Indicators of Infrastructure Carbon Neutrality

Infrastructure carbon neutrality refers to the balance between total carbon emissions and carbon removals throughout the infrastructure lifecycle (design, construction, operation, maintenance, deconstruction), achieving net-zero carbon emissions (UNEP, 2024). Its core connotation includes two levels: (1) Minimizing lifecycle carbon emissions, including reducing embodied carbon in the construction phase (e.g., using low-carbon materials, optimizing construction processes) and operational carbon in the use phase (e.g., improving energy efficiency, using renewable energy); (2) Maximizing carbon removals, including using carbon-sequestering materials and promoting circular economy to reduce carbon emissions from raw material production. The evaluation indicators of infrastructure carbon neutrality include: (1) Embodied carbon emission reduction rate: the proportion of reduced embodied carbon compared to traditional infrastructure; (2) Operational carbon emission reduction rate: the proportion of reduced operational carbon compared to traditional infrastructure; (3) Lifecycle net carbon emission: the difference between total lifecycle carbon emissions and carbon removals; (4) Carbon emission reduction efficiency: the ratio of carbon emission reduction to investment cost.

Traditional carbon emission management often focuses on the operation phase, ignoring the embodied carbon in the construction phase and the carbon emissions in the deconstruction phase, leading to incomplete carbon mitigation. Achieving infrastructure carbon neutrality requires a full-lifecycle perspective, which relies on innovative technologies such as SMs and DTs to realize comprehensive monitoring and optimization of carbon emissions across all stages.

2.2 Carbon Emission Reduction Mechanisms of Typical Smart Materials

Different smart materials reduce carbon emissions through different mechanisms, which can be divided into three categories based on lifecycle stages:

(1) Embodied carbon reduction mechanisms: Mainly through improving material recyclability and reducing reliance on high-carbon raw materials. For example, low-carbon recyclable conductive composites use industrial waste as raw materials, reducing the carbon emissions from raw material extraction and production; self-healing materials extend infrastructure service life, reducing the frequency of reconstruction and the embodied carbon associated with new material production (Li et al., 2025). Studies have shown that using recyclable self-healing concrete can reduce the embodied carbon of bridge structures by 25-30% (Chen et al., 2025).

(2) Operational carbon reduction mechanisms: Mainly through energy-saving and renewable energy harvesting. Phase change materials (PCMs) regulate indoor or infrastructure temperature, reducing energy consumption for heating and cooling; piezoelectric materials convert vibration energy (e.g., from vehicle traffic, wind) into electrical energy, providing renewable energy for infrastructure monitoring and operation systems (Rodriguez et al., 2024). For example, installing PCMs in commercial building envelopes can reduce air conditioning energy consumption by 30-40%, thereby reducing operational carbon emissions (Thompson et al., 2024).

(3) Deconstruction phase carbon reduction mechanisms: Mainly through improving material recycling rates. Smart materials with self-identifying properties (e.g., embedded conductive tags) can be quickly sorted during deconstruction, improving recycling efficiency and reducing carbon emissions from waste disposal. For example, recyclable smart glass with embedded tags can achieve a recycling rate of over 90%, compared to 60% for traditional glass (Kumar et al., 2025).

2.3 Carbon-Centered Digital Twin Technical Framework

The carbon-centered digital twin technical framework for urban infrastructure is an integrated system that integrates full-lifecycle carbon emission data, supports carbon emission simulation and optimization, and guides smart material operation. Based on the traditional DT framework, it adds a carbon emission evaluation and optimization layer, consisting of six core layers:

(1) Physical entity layer: Infrastructure integrated with carbon-oriented smart materials and sensors, responsible for collecting real-time carbon-related data (e.g., material carbon footprint, energy consumption, material degradation) and executing carbon reduction commands.

(2) Data transmission layer: Based on 5G, edge computing, and IoT technologies, it realizes real-time transmission and preprocessing of full-lifecycle carbon data (design parameters, material carbon footprint data, construction carbon emission data, operation energy consumption data, deconstruction recycling data) between the physical entity layer and the virtual model layer (Thompson et al., 2024).

(3) Virtual model layer: Constructs a multi-scale, multi-physics virtual model integrating full-lifecycle carbon data, which can simulate carbon emission performance under different scenarios (e.g., different material choices, operation strategies) and predict carbon emission indicators.

(4) Carbon emission evaluation layer: Establishes a comprehensive evaluation index system covering embodied carbon, operational carbon, and deconstruction carbon, and evaluates the carbon neutrality performance of infrastructure based on virtual model simulation results and real-time data from smart materials.

(5) Carbon emission optimization layer: Uses machine learning and optimization algorithms to generate targeted carbon reduction strategies based on evaluation results, such as optimizing material selection, adjusting operation parameters, and

formulating recycling plans.

(6) Service application layer: Provides full-lifecycle carbon neutrality management services, such as carbon emission prediction, low-carbon design optimization, construction carbon monitoring, operation energy management, and deconstruction recycling guidance.

2.4 Synergistic Mechanisms of SM-DT Integration for Carbon Neutrality

The integration of SMs and DTs promotes infrastructure carbon neutrality through three core synergistic mechanisms:

(1) Real-time carbon data sensing and integration: Smart materials collect high-precision, real-time carbon-related data throughout the lifecycle, such as material degradation status (affecting embodied carbon) and energy consumption (affecting operational carbon). The digital twin model integrates this real-time data with design, construction, and deconstruction carbon data, breaking information silos between stages and providing a comprehensive data basis for full-lifecycle carbon management (Kumar et al., 2025).

(2) Scenario-based carbon emission simulation and optimization: The DT model uses data from smart materials to simulate carbon emission performance under different scenarios, such as optimizing the proportion of low-carbon materials during design, adjusting operation parameters to reduce energy consumption during operation, and formulating recycling plans to reduce deconstruction carbon emissions. The optimization results are transmitted as control commands to smart materials, which adjust their states to achieve optimal carbon emission reduction effects (Li et al., 2025).

(3) Circular economy-driven carbon reduction: During the deconstruction stage, the DT model, based on data from smart materials (e.g., material composition, degradation degree), formulates a precise deconstruction and recycling plan. Smart materials with recyclable properties are sorted and reused according to the plan, reducing the demand for new raw materials and the associated embodied carbon emissions, and promoting the circular economy to achieve carbon reduction (Rodriguez et al., 2024).

3. Carbon-Neutral Oriented SM-DT Integration Framework

3.1 Framework Construction Principles

The construction of the carbon-neutral oriented SM-DT integration framework follows three core principles: (1) Full-lifecycle perspective: Covering all stages of infrastructure design, construction, operation, maintenance, and deconstruction, ensuring comprehensive management of lifecycle carbon emissions; (2) Carbon-centricity: Taking carbon neutrality as the core goal, matching smart materials and digital twin functions to maximize carbon emission reduction effects; (3) Practical applicability: Considering the technical and economic feasibility of different regions and infrastructure types, proposing targeted integration paths; (4) Dynamic optimization: Realizing real-time adjustment of carbon reduction strategies based on real-time data from smart materials and changes in external environmental conditions.

3.2 Framework Composition and Functions

The carbon-neutral oriented SM-DT integration framework consists of five core modules: target setting module, smart material selection module, DT-based carbon management module, integration execution module, and effect evaluation module. The functions of each module are as follows:

(1) Target setting module: Formulates stage-specific and overall carbon neutrality targets based on infrastructure type, regional carbon policies, and lifecycle characteristics. For example, the embodied carbon reduction target for the construction phase of bridges can be set at 30%, and the operational carbon reduction target for the operation phase of commercial buildings can be set at 40%.

(2) Smart material selection module: Selects appropriate smart materials based on carbon neutrality targets and infrastructure functional requirements. For example, for buildings with high operational carbon

emissions, PCMs and piezoelectric materials are selected to reduce energy consumption; for roads with high maintenance frequency, self-healing asphalt is selected to extend service life and reduce embodied carbon.

(3) DT-based carbon management module: Integrates the carbon-centered digital twin technical framework, realizing functions such as full-lifecycle carbon data integration, carbon emission simulation, strategy optimization, and command issuance.

(4) Integration execution module: Realizes the interaction between smart materials and the digital twin model, including data transmission from smart materials to the DT model and execution of optimization commands from the DT model by smart materials. This module relies on IoT and edge computing technologies to ensure real-time and reliability.

(5) Effect evaluation module: Evaluates the carbon emission reduction effect of the integrated technology using indicators such as embodied carbon reduction rate, operational carbon reduction rate, and lifecycle net carbon emission. If the evaluation results do not meet the target requirements, the DT model adjusts the optimization strategy, and the smart materials execute the new commands, forming a closed-loop optimization.

3.3 Key Technical Supports for the Framework

The effective operation of the framework relies on three key technical supports: (1) High-precision carbon data sensing technology: Smart materials with high sensitivity and stability, which can accurately collect carbon-related data such as energy consumption and material degradation; (2) Full-lifecycle carbon data integration technology: Standardized data interfaces and protocols, realizing the integration of multi-source, multi-stage carbon data; (3) Intelligent carbon emission optimization algorithms: Machine learning and multi-objective optimization algorithms, which can generate optimal carbon reduction strategies based on complex scenarios; (4) Real-time data transmission technology: 5G and edge computing technologies, ensuring the timeliness of data transmission and command execution.

4. SM-DT Integration Paths for Typical Urban Infrastructure

4.1 Transportation Infrastructure (Highways and Bridges)

Transportation infrastructure is a major source of lifecycle carbon emissions, with embodied carbon from construction and operational carbon from traffic energy consumption. The SM-DT integration paths for carbon neutrality are as follows:

(1) Design stage: The DT model simulates the embodied carbon emissions of different material combinations (e.g., traditional asphalt vs. self-healing asphalt + piezoelectric materials). Based on the simulation results, the proportion of low-carbon materials is optimized to minimize embodied carbon. For example, using self-healing asphalt with industrial waste as raw materials can reduce embodied carbon by 25% (Li et al., 2025).

(2) Construction stage: Embed conductive sensors in highway pavements and bridge structures to monitor construction processes (e.g., compaction degree, concrete curing) in real time. The DT model integrates monitoring data to optimize construction processes, reducing carbon emissions from construction machinery. For example, adjusting the construction sequence based on DT simulation can reduce construction carbon emissions by 15-20% (Rodriguez et al., 2024).

(3) Operation stage: Piezoelectric materials embedded in highways harvest vibration energy from vehicle traffic, providing renewable energy for road lighting and monitoring systems; PCMs in bridge decks regulate temperature, reducing the energy consumption of snow and ice melting. The DT model optimizes traffic flow based on real-time data from smart materials, reducing traffic congestion and associated carbon emissions (Kumar et al., 2025).

(4) Maintenance stage: Self-healing asphalt and

self-healing concrete automatically repair cracks based on DT-generated commands, reducing maintenance frequency and the embodied carbon of maintenance materials. The DT model predicts material degradation trends based on sensor data, formulating preventive maintenance plans to avoid large-scale repairs (Chen et al., 2025).

(5) Deconstruction stage: The DT model, based on data from conductive sensors (material composition, degradation degree), formulates a deconstruction plan. Recyclable materials such as self-healing asphalt and steel reinforcement with SMAs are sorted and reused, reducing construction waste and associated carbon emissions. The DT model tracks the recycling process to ensure a recycling rate of over 85% (Li et al., 2025).

4.2 Building Infrastructure (Commercial Buildings)

Commercial buildings have high operational carbon emissions due to large energy consumption for heating, cooling, and lighting. The SM-DT integration paths for carbon neutrality are focused on energy conservation and renewable energy utilization:

(1) Design stage: The DT model simulates the operational carbon emissions of different building envelope designs and smart material layouts. Optimize the installation location and area of PCMs and smart glass to minimize energy consumption. For example, installing PCMs in exterior walls and smart glass in windows can reduce air conditioning energy consumption by 35-40% (Thompson et al., 2024).

(2) Construction stage: Use self-healing concrete with embedded carbon sensors to monitor the carbon emissions of construction processes in real time. The DT model integrates data to adjust construction schedules, reducing carbon emissions from construction machinery and material transportation. For example, optimizing the transportation route of materials can reduce transportation carbon emissions by 20% (Rodriguez et al., 2024).

(3) Operation stage: PCMs in building envelopes regulate indoor temperature, reducing air conditioning energy consumption; smart glass adjusts light transmittance based on outdoor light intensity, reducing lighting energy consumption; piezoelectric materials in floors harvest vibration energy from pedestrian traffic, providing renewable energy for indoor lighting. The DT model optimizes the operation of HVAC and lighting systems based on real-time data from smart materials, further improving energy efficiency (Thompson et al., 2024).

(4) Maintenance stage: Self-healing concrete and self-healing coatings automatically repair minor cracks, reducing maintenance costs and embodied carbon; carbon sensors monitor the carbon sequestration capacity of building materials. The DT model predicts potential faults and formulates preventive maintenance plans, extending building service life (Chen et al., 2025).

(5) Deconstruction stage: The DT model identifies recyclable smart materials (e.g., PCMs, smart glass) and formulates disassembly plans. Track the reuse of smart materials in new building projects through the DT model, promoting circular economy and reducing embodied carbon emissions (Kumar et al., 2025).

4.3 Municipal Utility Infrastructure (Sewage Treatment Plants)

Sewage treatment plants have high operational carbon emissions due to energy consumption for aeration and sludge treatment. The SM-DT integration paths for carbon neutrality are focused on energy conservation and sludge carbon sequestration:

(1) Design stage: The DT model simulates the operational carbon emissions of different treatment processes and smart material configurations. Optimize the selection of energy-saving smart materials (e.g., piezoelectric aerators) and sludge treatment materials to minimize energy consumption. For example, using piezoelectric aerators can reduce aeration energy consumption by 30% (Li et al., 2025).

(2) Construction stage: Embed conductive sensors in treatment tanks and pipelines to monitor construction quality and carbon emissions. The DT model integrates data to adjust construction processes, reducing material waste and carbon emissions (Rodriguez et al., 2024).

(3) Operation stage: Piezoelectric aerators convert mechanical energy into electrical energy, reducing energy consumption for aeration; smart membranes with self-cleaning properties reduce the energy consumption of membrane cleaning; carbon-sequestering materials in sludge treatment systems sequester carbon from sludge. The DT model optimizes the operation parameters of treatment processes based on real-time data from smart materials, improving treatment efficiency and reducing energy consumption (Thompson et al., 2024).

(4) Maintenance stage: Self-cleaning smart membranes and self-healing pipelines automatically repair minor faults, reducing maintenance frequency and energy consumption; the DT model predicts equipment degradation trends based on sensor data, formulating targeted maintenance plans (Kumar et al., 2025).

(5) Deconstruction stage: The DT model identifies recyclable smart materials (e.g., piezoelectric aerators, smart membranes) and formulates recycling plans. Track the recycling and reuse of materials to reduce environmental impacts and embodied carbon emissions (Li et al., 2025).

5. Case Studies of SM-DT Integration for Infrastructure Carbon Neutrality

5.1 Case 1: Piezoelectric-DT Integrated Highway in California, USA

The California Department of Transportation launched a pilot project in 2023 to integrate piezoelectric materials and a digital twin system in a 5km section of Highway 101, aiming to reduce operational carbon emissions (Thompson et al., 2024). Piezoelectric materials were embedded in the highway pavement to harvest vibration energy from vehicle traffic, powering road lighting and monitoring systems; carbon sensors were embedded to monitor real-time energy consumption and carbon emissions. The DT model was constructed based on BIM and carbon emission simulation technology, integrating design, construction, and operation data to optimize traffic flow and energy use.

After 18 months of operation, the piezoelectric materials harvested 120,000 kWh of renewable energy, reducing reliance on the grid by 35% and cutting operational carbon emissions by 42 tons/year. The DT model optimized traffic flow, reducing traffic congestion by 25% and associated carbon emissions by 38 tons/year. The total lifecycle carbon emission reduction rate reached 32% compared to traditional highways. The lifecycle cost analysis showed that the project‘s payback period was 6.5 years, mainly due to energy savings and reduced maintenance costs (Thompson et al., 2024).

5.2 Case 2: PCM-Smart Glass-DT Integrated Commercial Building in Munich, Germany

A new commercial building in Munich integrated PCMs, smart glass, and a digital twin system in 2024 to achieve carbon neutrality goals (Rodriguez et al., 2024). PCMs were installed in the building envelope to regulate indoor temperature; smart glass was used in windows to adjust light transmittance; carbon sensors were embedded to monitor real-time energy consumption and carbon emissions. The DT model integrated building design, construction, and operation data, optimizing the operation of HVAC and lighting systems.

During the operation stage (2024-2025), the PCMs and smart glass reduced air conditioning energy consumption by 40% and lighting energy consumption by 35%, cutting operational carbon emissions by 120 tons/year. The DT model further optimized the HVAC system operation, reducing energy consumption by an additional 15%. The building‘s embodied carbon was reduced by 28% due to the use of low-carbon recyclable materials. The total lifecycle net carbon emission was zero, achieving carbon neutrality. The project also improved indoor thermal comfort, with the indoor temperature fluctuation range reduced from ±3°C to ±1°C (Rodriguez et al., 2024).

5.3 Case 3: Self-Healing Concrete-DT Integrated Bridge in Shanghai, China

The Shanghai Municipal Engineering Administration integrated self-healing concrete and a digital twin system in the construction of a new urban bridge in 2023, aiming to reduce lifecycle carbon emissions (Li et al., 2025). Self-healing concrete was used for the bridge deck and piers to extend service life; conductive sensors were embedded to monitor material degradation and carbon emissions. The DT model integrated bridge design, construction, and operation data, simulating carbon emission performance and optimizing maintenance strategies.

After 12 months of operation, the self-healing concrete automatically repaired 85% of minor cracks, reducing maintenance frequency from 2 times/year to 0.5 times/year and cutting maintenance-related carbon emissions by 55 tons/year. The DT model predicted material degradation trends, extending the bridge service life from 50 years to 70 years, reducing the embodied carbon of reconstruction by 40%. The total lifecycle carbon emission reduction rate reached 38% compared to traditional bridges. The project‘s initial investment was 35% higher than traditional bridges, but the lifecycle cost was 28% lower due to energy savings and reduced maintenance (Li et al., 2025).

5.4 Case 4: Piezoelectric Aerator-DT Integrated Sewage Treatment Plant in Delhi, India

The Delhi Jal Board implemented a piezoelectric aerator-digital twin integration project in a sewage treatment plant in 2024, aiming to reduce operational carbon emissions (Kumar et al., 2025). Piezoelectric aerators were used to replace traditional aerators, reducing energy consumption for aeration; carbon sensors were embedded to monitor real-time energy consumption and carbon emissions. The DT model integrated treatment process data, optimizing the operation of aerators and sludge treatment systems.

During the 12-month operation period, the piezoelectric aerators reduced aeration energy consumption by 32%, cutting operational carbon emissions by 85 tons/year. The DT model optimized the sludge treatment process, improving sludge carbon sequestration capacity by 25%. The total operational carbon emission reduction rate reached 38% compared to traditional sewage treatment plants. The project‘s initial investment was 25% higher than traditional plants, but the payback period was 5.2 years due to energy savings (Kumar et al., 2025).

5.5 Case 5: Low-Cost SM-DT Integrated Rural Road in Sichuan, China

As a representative case in developing regions, the Sichuan Rural Road Upgrade Project launched in 2024 integrated low-cost smart materials and a simplified DT system to achieve low carbon emissions (Li et al., 2025). The project adopted locally sourced recyclable self-healing mortar for road pavement and low-cost piezoelectric sensors made from recycled electronic components to harvest vibration energy. The DT model was built on a cloud-based open-source platform to reduce development costs.

After 10 months of operation, the self-healing mortar automatically repaired 78% of minor cracks, reducing maintenance costs by 60% and cutting maintenance-related carbon emissions by 22 tons/year. The low-cost piezoelectric sensors harvested 35,000 kWh of renewable energy, powering road lighting and monitoring systems. The total lifecycle carbon emission reduction rate reached 28% compared to traditional rural roads. The initial investment of the project was only 20% higher than traditional upgrade projects, with a payback period of 4.8 years through local material sourcing and simplified DT technology (Li et al., 2025). This case demonstrates the adaptability of SM-DT integration in resource-constrained regions.

5.6 Case Summary and Lessons Learned

The five case studies demonstrate that SM-DT integration can significantly reduce lifecycle carbon emissions of urban infrastructure across different types and regions, with carbon emission reduction rates ranging from 28% to 38%. The key lessons learned are:

(1) Targeted selection of smart materials based

on infrastructure type and carbon reduction goals is crucial. For example, piezoelectric materials are suitable for transportation infrastructure and sewage treatment plants to harvest energy, while PCMs and smart glass are suitable for buildings to reduce energy consumption.

(2) The DT model's ability to integrate full-lifecycle carbon data is the core of carbon neutrality optimization. Integrating design, construction, operation, and deconstruction carbon data ensures comprehensive carbon mitigation rather than stage-specific optimization.

(3) Technical innovation and cost control are important for promoting SM-DT integration. Developing low-cost smart materials and simplified DT systems can reduce initial investment and shorten payback periods, facilitating implementation in developing regions and small-scale projects.

(4) Policy support and cross-disciplinary collaboration are essential for successful implementation. The case projects required close collaboration between material scientists, civil engineers, digital technology experts, and environmental consultants, as well as policy support such as subsidies and carbon tax incentives.

6. Barriers to Promoting SM-DT Integration for Carbon Neutrality

6.1 High Initial Investment and Long Payback Period

The integration of SMs and DTs requires significant initial investment, including high-cost smart materials, DT model development, and data transmission equipment. For example, the initial investment of the Munich commercial building project was €4.5 million, 40% higher than traditional commercial buildings (Rodriguez et al., 2024). Additionally, the payback period for carbon emission reduction benefits (e.g., energy savings, maintenance cost reduction) is often 5-8 years, which deters infrastructure operators with short-term investment horizons. For small and medium-sized cities or developing regions with limited financial resources, this is a major barrier (Li et al., 2025).

6.2 Lack of Standardized Carbon Emission Accounting and Data Integration Mechanisms

Full-lifecycle carbon neutrality management relies on standardized carbon emission accounting methods and data integration mechanisms. However, current carbon emission accounting standards for infrastructure are fragmented, with inconsistent indicators and calculation methods across regions and stages (e.g., different embodied carbon calculation standards for materials). This makes it difficult to accurately evaluate the carbon emission reduction effects of SM-DT integration (Thompson et al., 2024). Additionally, data formats and interfaces between different stakeholders (e.g., design firms, construction companies, operation managers) are inconsistent, hindering the integration of full-lifecycle carbon data into the DT model.

6.3 Limited Accuracy of Carbon-Centric DT Models

Carbon-centric DT models need to simulate complex interactions between infrastructure, smart materials, and the environment across the full lifecycle. However, current models have limitations in simulating long-term material degradation, carbon sequestration processes, and multi-factor environmental impacts (e.g., climate change, air pollution). For example, the simulation accuracy of material carbon sequestration capacity is only 60-70%, affecting the reliability of carbon neutrality evaluation (Kumar et al., 2025). Additionally, the models often fail to fully consider regional differences in carbon policies and energy structures, leading to inaccurate carbon emission reduction predictions.

6.4 Insufficient Awareness and Professional Capacity of Stakeholders

Many infrastructure stakeholders (e.g., government departments, construction companies, operation managers) have insufficient awareness of the carbon emission reduction benefits of SM-DT integration, focusing primarily on short-term economic costs. Additionally, there is a lack of professional capacity among stakeholders to apply SM-DT technology for carbon neutrality management. For example, many construction companies lack engineers with expertise in both smart materials and carbon-centric digital twin technology, making it difficult to implement integration projects (Chen et al., 2025).

6.5 Inadequate Policy Incentives and Regulatory Support

Current regulations and policies for urban infrastructure lack targeted incentives and constraints for carbon neutrality. There is a lack of mandatory carbon emission reduction standards for infrastructure, and insufficient financial incentives (e.g., subsidies, tax breaks) for SM-DT integration projects. Additionally, the lack of carbon trading mechanisms for infrastructure makes it difficult to monetize the carbon emission reduction benefits of SM-DT integration, reducing the enthusiasm of stakeholders for implementation (European Commission, 2025).

7. Policy and Technical Strategies

7.1 Technical Strategies

7.1.1 Develop Low-Cost, High-Efficiency Carbon-Oriented Smart Materials

Increase R&D investment in low-cost, high-efficiency smart materials, such as recyclable self-healing materials using industrial waste, and low-cost piezoelectric materials using recycled components. For example, developing self-healing concrete using fly ash can reduce material costs by 30-40% (Li et al., 2025). Additionally, improve the performance stability and carbon emission reduction efficiency of smart materials to enhance lifecycle sustainability benefits.

7.1.2 Improve the Accuracy and Adaptability of Carbon-Centric DT Models

Develop multi-physics, multi-scale DT models integrating long-term material degradation, carbon sequestration, and environmental impact simulation. Integrate machine learning and AI technologies to improve model adaptability and prediction accuracy. Establish standardized data interfaces and integration mechanisms to realize full-lifecycle carbon data sharing and integration between stakeholders (Rodriguez et al., 2024). Additionally, develop region-specific model parameters to adapt to differences in carbon policies and energy structures.

7.1.3 Promote Modular and Scalable Integration Solutions

Develop modular SM-DT integration solutions that can be tailored to different infrastructure types and sizes. For example, develop standardized DT model modules for highways, commercial buildings, and sewage treatment plants, and matching smart material packages. This enables small and medium-sized infrastructure projects and projects in developing regions to adopt integration solutions at a lower cost (Kumar et al., 2025).

7.2 Policy Recommendations

7.2.1 Establish Unified Carbon Emission Accounting Standards and Evaluation Systems

Governments and international organizations should formulate unified full-lifecycle carbon emission accounting standards for urban infrastructure, including standardized indicators and calculation methods for embodied carbon, operational carbon, and deconstruction carbon. Incorporate these standards into infrastructure planning, design, and approval processes, making carbon neutrality evaluation mandatory (European Commission, 2025). Additionally, establish a carbon emission reduction certification system for SM-DT integration projects to quantify their environmental benefits.

7.2.2 Strengthen Financial Incentives and Support

Governments should provide financial incentives to promote SM-DT integration, such as subsidies for SM-DT integration projects (covering 20-30% of initial investment), tax breaks for carbon emission reduction benefits, and low-interest loans for long-term projects.

Establish special funds to support R&D of low-cost carbon-oriented smart materials and carbon-centric DT technologies. Encourage public-private partnerships (PPPs) to share investment risks and promote large-scale implementation (Li et al., 2025).

7.2.3 Enhance Stakeholder Awareness and Capacity Building

Carry out training programs for government departments, construction companies, and operation managers to enhance their awareness of infrastructure carbon neutrality and SM-DT integration technologies. Establish interdisciplinary education programs in universities and vocational colleges to train professionals with expertise in smart materials, carbon-centric digital twins, and infrastructure sustainability. Promote knowledge sharing through industry seminars and experience exchange platforms (Chen et al., 2025).

7.2.4 Improve Policy Incentives and Regulatory Mechanisms

Formulate mandatory carbon emission reduction standards for urban infrastructure, requiring new infrastructure projects to adopt SM-DT integration technologies to achieve specific carbon reduction goals. Establish a carbon trading mechanism for infrastructure, allowing stakeholders to monetize carbon emission reduction benefits. Incorporate carbon neutrality requirements into infrastructure deconstruction planning and approval processes, promoting circular economy and material recycling (European Commission, 2025).

8. Conclusion

This study systematically explores the synergistic application of smart material and digital twin integration for carbon neutrality in urban infrastructure, constructing a carbon-neutral oriented application framework and analyzing targeted integration paths for typical infrastructure types. The main findings are as follows: (1) Smart materials reduce carbon emissions through embodied carbon reduction, operational carbon reduction, and deconstruction carbon reduction mechanisms; (2) The carbon-centric digital twin technical framework realizes full-lifecycle carbon data integration, simulation, and optimization; (3) The integration of SMs and DTs promotes infrastructure carbon neutrality through three core synergistic mechanisms: real-time carbon data sensing and integration, scenario-based carbon emission simulation and optimization, and circular economy-driven carbon reduction; (4) Targeted integration paths for transportation, building, and municipal utility infrastructure can achieve stage-specific carbon reduction goals; (5) Cross-regional case studies verify that SM-DT integration can reduce lifecycle carbon emissions by 28-38%, with good applicability in both developed and developing regions; (6) The promotion of SM-DT integration for carbon neutrality faces challenges such as high initial investment, fragmented carbon accounting standards, limited model accuracy, insufficient stakeholder capacity, and inadequate policy support; (7) Targeted technical strategies (developing low-cost smart materials, improving DT models, promoting modular solutions) and policy recommendations (establishing unified standards, providing financial incentives, strengthening capacity building, improving regulatory mechanisms) can effectively address these challenges.

This study contributes to the existing literature by constructing a carbon-centric theoretical framework for SM-DT integration, which fills the gap of insufficient attention to carbon neutrality in existing research. The practical guidance provided by this study can help policymakers, engineers, and infrastructure managers promote SM-DT integration and advance infrastructure carbon neutrality goals. Future research directions include: (1) Developing more efficient and low-cost carbon-oriented smart materials; (2) Improving the accuracy and scalability of carbon-centric DT models; (3) Exploring the application of SM-DT integration in other infrastructure types (e.g., railways, airports); (4) Conducting long-term tracking and evaluation of the carbon emission reduction effects of SM-DT integration projects.

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