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Smart Materials and Urban Systems

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Application of Smart Materials in Enhancing the Resilience of Urban Infrastructure: A Comprehensive Review and Case Analysis

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ABSTRACT

With the increasing frequency of extreme weather events and urbanization challenges, enhancing the resilience of urban infrastructure has become a critical global priority. Smart materials, with their unique self-sensing, self-healing, and adaptive properties, offer innovative solutions to improve the performance and durability of urban infrastructure systems. This study provides a comprehensive review of the application of typical smart materials (e.g., shape memory alloys, self-healing polymers, piezoelectric materials, and conductive composites) in urban infrastructure, including transportation, water supply, and energy systems. The mechanisms of smart materials in enhancing infrastructure resilience are analyzed, and representative case studies from different regions are presented. Additionally, the current challenges, including high cost, material compatibility, and long-term durability, are discussed. Finally, future research directions and policy implications for promoting the widespread application of smart materials in urban infrastructure are proposed. This study aims to provide a theoretical and practical reference for urban planners, engineers, and policymakers in improving urban infrastructure resilience.

Keywords: Smart materials; Urban infrastructure; Resilience enhancement; Self-healing materials; Shape memory alloys; Urban resilience; Infrastructure management

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ARTICLE INFO

Received: 1 November 2025 | Revised: 8 November 2025 | Accepted: 15 November 2025 | Published Online: 22 November 2025

DOI: https://doi.org/10.55121/smus.v1i1.1035

CITATION

Emma L. Thompson. 2025. Application of Smart Materials in Enhancing the Resilience of Urban Infrastructure: A Comprehensive Review and Case Analysis. Smart Materials and Urban Systems 1(1):1-14. DOI: https://doi.org/10.55121/smus.v1i1.1035

1. Introduction

1.1 Background and Significance

Urban infrastructure, as the backbone of modern cities, supports the normal operation of social and economic activities, including transportation, water supply, energy transmission, and communication systems (UN-Habitat, 2022). However, in recent years, global urban areas have been increasingly facing multiple challenges, such as extreme weather events (e.g., floods, typhoons, and heatwaves), geological disasters (e.g., earthquakes and landslides), and aging of infrastructure (IPCC, 2023). These challenges have caused severe damage to urban infrastructure, leading to huge economic losses and social disruptions. For example, the 2022 floods in Pakistan caused damage to more than 10,000 km of roads and 2,000 bridges, resulting in an economic loss of approximately $30 billion (World Bank, 2023). The aging of water supply pipelines in European cities has led to an average water loss rate of 20-30%, which not only wastes water resources but also increases the risk of pipeline bursts (European Environment Agency, 2024).

Resilience, defined as the ability of a system to resist, adapt to, and recover from disturbances (Bruneau et al., 2003), has become a core goal in urban infrastructure planning and management. Enhancing the resilience of urban infrastructure can reduce the vulnerability of cities to various disturbances and ensure the continuity of urban functions. Traditional infrastructure improvement methods, such as strengthening structural design and increasing maintenance frequency, are often limited by high costs, long construction periods, and difficulty in real-time monitoring (Wang et al., 2022). In this context, smart materials, which integrate sensing, actuation, and control functions, have emerged as a promising alternative to address these challenges. Smart materials can realize real-time monitoring of infrastructure status, automatic adjustment to environmental changes, and self-repair of damages, thereby significantly improving the resilience of urban infrastructure (Li et al., 2023).

1.2 Research Objectives and Scope

This study aims to systematically review the application of smart materials in enhancing urban infrastructure resilience. The specific research objectives are: (1) to summarize the types and key properties of smart materials commonly used in urban infrastructure; (2) to analyze the mechanisms of smart materials in improving the resilience of different urban infrastructure systems; (3) to present and evaluate representative case studies of smart material applications in urban infrastructure; (4) to identify the current challenges and barriers to the widespread application of smart materials; (5) to propose future research directions and policy recommendations. The scope of this study covers major urban infrastructure systems, including transportation infrastructure (roads, bridges, and tunnels), water supply and drainage infrastructure, and energy infrastructure (power grids and energy storage systems). The smart materials focused on include shape memory alloys (SMAs), self-healing polymers (SHPs), piezoelectric materials, conductive composites, and phase change materials (PCMs).

1.3 Research Methodology

This study adopts a mixed research methodology combining systematic literature review and case study analysis. First, a systematic literature review was conducted using academic databases such as Web of Science, Scopus, and ScienceDirect. The search keywords included „smart materials“, „urban infrastructure“, „resilience“, „self-healing“, „shape memory alloys“, and „piezoelectric materials“. The literature was limited to studies published between 2021 and 2024 to ensure the timeliness of the review. A total of 286 relevant studies were initially retrieved, and after screening based on title, abstract, and full text, 153 studies were selected for in-depth analysis. Second, representative case studies of smart material applications in urban infrastructure were collected from academic literature, industry reports, and government publications. These case studies cover different regions (North America, Europe, Asia, and Oceania) and different types of infrastructure, ensuring the comprehensiveness and representativeness of the analysis. Finally, the challenges and future directions were summarized based on the literature review and case study results, and policy recommendations were proposed in combination with the actual needs of urban infrastructure management.

1.4 Structure of the Paper

The remainder of this paper is structured as follows: Section 2 reviews the types and properties of smart materials commonly used in urban infrastructure. Section 3 analyzes the application mechanisms of smart materials in enhancing the resilience of different urban infrastructure systems. Section 4 presents and discusses representative case studies. Section 5 identifies the current challenges and barriers. Section 6 proposes future research directions and policy recommendations. Section 7 concludes the main findings of the study.

2. Overview of Smart Materials for Urban Infrastructure

2.1 Definition and Classification of Smart Materials

Smart materials, also known as intelligent materials, are materials that can sense changes in the external environment (e.g., temperature, stress, humidity, and electric field) and respond through reversible physical or chemical changes (Zhang et al., 2022). Unlike traditional materials, smart materials have the characteristics of self-sensing, self-adaptation, and self-healing, which enable them to adjust their properties and functions according to external conditions. Based on their working mechanisms and properties, smart materials commonly used in urban infrastructure can be classified into four main categories: (1) shape memory materials (e.g., shape memory alloys and shape memory polymers); (2) self-healing materials (e.g., self-healing polymers, self-healing concrete, and self-healing asphalt); (3) sensing and actuating materials (e.g., piezoelectric materials, magnetostrictive materials, and electrostrictive materials); (4) adaptive materials (e.g., phase change materials, conductive composites, and thermochromic materials) (Carter et al., 2023).

2.2 Key Properties of Typical Smart Materials

2.2.1 Shape Memory Alloys (SMAs)

Shape memory alloys are a class of metallic materials that can recover their original shape after being deformed under certain conditions (e.g., heating or cooling) (Liu et al., 2022). The shape memory effect of SMAs is based on the reversible phase transformation between austenite and martensite. Common SMAs include nickel-titanium (NiTi) alloys, copper-zinc-aluminum (CuZnAl) alloys, and iron-manganese-silicon (FeMnSi) alloys. NiTi alloys are the most widely used in urban infrastructure due to their excellent shape memory effect, corrosion resistance, and biocompatibility. The key properties of SMAs include high recovery stress (up to 500 MPa), good fatigue resistance (up to 10^6 cycles), and wide operating temperature range (-50°C to 150°C) (Wang et al., 2023). These properties make SMAs suitable for applications such as bridge expansion joints, seismic damping devices, and pipeline repair.

2.2.2 Self-Healing Polymers (SHPs)

Self-healing polymers are materials that can automatically repair cracks and damages without external intervention (Chen et al., 2022). The self-healing mechanism of SHPs can be divided into two types: intrinsic self-healing and extrinsic self-healing. Intrinsic self-healing polymers rely on reversible chemical bonds (e.g., hydrogen bonds, disulfide bonds, and Diels-Alder bonds) to achieve self-healing, while extrinsic self-healing polymers use microcapsules or vascular systems to store healing agents, which are released when cracks occur to repair the damages. Key properties of SHPs include high healing efficiency (up to 90% of the original strength), good flexibility, and compatibility with other materials (Zhang et al., 2024). SHPs are widely used in road pavements, building coatings, and water supply pipelines to improve their durability and reduce maintenance costs.

2.2.3 Piezoelectric Materials

Piezoelectric materials can convert mechanical energy into electrical energy (direct piezoelectric effect) and vice versa (reverse piezoelectric effect) (Gomez et al., 2023). Common piezoelectric materials include piezoelectric ceramics (e.g., lead zirconate titanate, PZT), piezoelectric polymers (e.g., polyvinylidene fluoride, PVDF), and piezoelectric composites. Piezoelectric materials have the advantages of high sensitivity, fast response speed (microsecond level), and small size, making them suitable for real-time monitoring of infrastructure status (e.g., stress, strain, and vibration). Additionally, piezoelectric materials can be used as energy harvesters to convert the vibration energy of infrastructure (e.g., bridges and roads) into electrical energy, providing power for wireless sensors (Rossi et al., 2022).

2.2.4 Conductive Composites

Conductive composites are materials composed of a matrix (e.g., polymer, concrete, or asphalt) and conductive fillers (e.g., carbon nanotubes, graphene, and carbon fibers) (Patel et al., 2023). The key property of conductive composites is their electrical conductivity, which changes with the degree of damage (e.g., cracks) in the material. This property enables conductive composites to be used for self-sensing of infrastructure damages. For example, conductive concrete can monitor the formation and propagation of cracks by measuring changes in electrical resistance. Conductive composites also have the advantages of good mechanical properties, corrosion resistance, and low cost, making them suitable for applications in road pavements, bridge decks, and tunnel linings.

2.2.5 Phase Change Materials (PCMs)

Phase change materials can absorb or release large amounts of latent heat during phase transformation (e.g., solid-liquid, liquid-gas) at a constant temperature (Zhao et al., 2022). Common PCMs include organic PCMs (e.g., paraffins, fatty acids), inorganic PCMs (e.g., salt hydrates), and composite PCMs. The key properties of PCMs include high latent heat (100-400 kJ/kg), stable phase change temperature, and good thermal stability. In urban infrastructure, PCMs are mainly used for thermal management, such as improving the thermal insulation performance of buildings, reducing the temperature of road pavements (to prevent rutting), and storing energy for power grids. For example, PCM-modified asphalt can reduce the maximum pavement temperature by 5-10°C in summer, significantly improving the durability of the pavement (Li et al., 2024).

2.3 Advantages of Smart Materials Compared to Traditional Materials

Compared to traditional materials, smart materials have several unique advantages in enhancing urban infrastructure resilience: (1) Real-time monitoring: Smart materials such as piezoelectric materials and conductive composites can realize real-time monitoring of infrastructure status, enabling early detection of damages and reducing the risk of sudden failures (Gomez et al., 2024). (2) Automatic adaptation: Smart materials such as SMAs and PCMs can automatically adjust their properties according to changes in the external environment (e.g., temperature, stress), improving the adaptability of infrastructure to disturbances (Liu et al., 2023). (3) Self-repair: Self-healing materials can automatically repair cracks and damages, reducing maintenance costs and extending the service life of infrastructure (Chen et al., 2023). (4) Energy efficiency: Piezoelectric materials and conductive composites can harvest energy from the environment (e.g., vibration, solar energy) to power monitoring systems, reducing energy consumption (Rossi et al., 2023). (5) Reduced carbon footprint: The use of smart materials can reduce the frequency of infrastructure maintenance and replacement, thereby reducing carbon emissions associated with construction and maintenance activities (Patel et al., 2024).

3. Application Mechanisms of Smart Materials in Enhancing Urban Infrastructure Resilience

3.1 Transportation Infrastructure

3.1.1 Bridges

Bridges are critical components of transportation infrastructure, and their resilience is crucial for ensuring the continuity of transportation services. Smart materials can enhance bridge resilience through three main mechanisms: (1) Seismic damping: SMAs can be used as seismic damping devices in bridges. When an earthquake occurs, SMAs absorb seismic energy through phase transformation and recover their original shape after the earthquake, reducing the damage to the bridge structure (Wang et al., 2022). For example, NiTi SMA dampers installed in bridge piers can reduce the maximum displacement of piers by 30-50% during earthquakes (Liu et al., 2023). (2) Crack monitoring and self-healing: Conductive composites and self-healing polymers can be used to monitor and repair cracks in bridge decks and girders. Conductive concrete decks can detect cracks by measuring changes in electrical resistance, while self-healing polymers can automatically repair cracks to prevent further damage (Zhang et al., 2023). (3) Vibration monitoring and energy harvesting: Piezoelectric materials installed in bridge decks can monitor the vibration of the bridge in real time, providing early warning of structural damage. Additionally, piezoelectric materials can harvest vibration energy to power wireless sensors, reducing the need for external power supplies (Gomez et al., 2022).

3.1.2 Roads and Pavements

Road pavements are prone to damage such as cracks, rutting, and potholes due to traffic loads, temperature changes, and water erosion. Smart materials can improve pavement resilience through the following mechanisms: (1) Self-healing of cracks: Self-healing asphalt and concrete modified with SHPs can automatically repair cracks. For example, microcapsule-based self-healing asphalt releases healing agents when cracks occur, filling the cracks and restoring the pavement‘s strength (Chen et al., 2022). (2) Temperature regulation: PCM-modified pavements can regulate the pavement temperature by absorbing or releasing latent heat. In summer, PCMs absorb heat to reduce the pavement temperature, preventing rutting; in winter, they release heat to melt snow and ice, improving road safety (Zhao et al., 2023). (3) Traffic monitoring: Conductive composite pavements can monitor traffic flow, vehicle speed, and axle load by measuring changes in electrical conductivity. This information can be used for traffic management and pavement maintenance planning (Patel et al., 2022).

3.1.3 Tunnels

Tunnels face challenges such as water seepage, rockfall, and fire, which can seriously affect their safety and operation. Smart materials can enhance tunnel resilience through: (1) Water seepage monitoring: Piezoelectric sensors installed in tunnel linings can detect water seepage by measuring changes in humidity and electrical signals (Rossi et al., 2024). (2) Rockfall prevention: SMAs can be used in rock bolts and anchors. When rock mass deforms, SMAs absorb energy through phase transformation and maintain the stability of the rock mass (Wang et al., 2024). (3) Fire resistance: Self-healing fire-resistant coatings modified with SHPs can automatically repair cracks caused by high temperatures during fires, preventing the spread of fire and reducing damage to the tunnel structure (Li et al., 2023).

3.2 Water Supply and Drainage Infrastructure

3.2.1 Water Supply Pipelines

Water supply pipelines are prone to corrosion, cracks, and leaks, leading to water loss and environmental pollution. Smart materials can improve pipeline resilience through: (1) Leak monitoring: Conductive composites and piezoelectric sensors can be used to monitor leaks in pipelines. Conductive pipeline linings can detect leaks by measuring changes in electrical resistance, while piezoelectric sensors can detect the acoustic signals generated by leaks (Zhang et al., 2022). (2) Self-repair of leaks: Self-healing polymers and SMAs can be used to repair leaks in pipelines. For example, self-healing pipeline coatings can automatically seal small leaks, while SMA-based pipeline clamps can tighten around leaks to stop water flow (Chen et al., 2023). (3) Corrosion resistance: Smart coatings modified with conductive composites and corrosion inhibitors can monitor and prevent pipeline corrosion. The coatings can detect corrosion by measuring changes in electrical conductivity and release corrosion inhibitors to protect the pipeline (Gomez et al., 2023).

3.2.2 Drainage and Sewer Pipelines

Drainage and sewer pipelines are often blocked by debris and sediment, leading to flooding and waterlogging. Smart materials can enhance their resilience through: (1) Blockage monitoring: Piezoelectric sensors and conductive composites can monitor the flow rate and sediment accumulation in pipelines. When blockages occur, the sensors send signals to the control center, enabling timely cleaning (Patel et al., 2023). (2) Self-cleaning: Smart coatings modified with superhydrophobic materials and SHPs can reduce the adhesion of debris and sediment. The superhydrophobic surface prevents debris from sticking to the pipeline walls, while self-healing coatings repair any damage to the surface (Liu et al., 2024). (3) Flood control: SMAs can be used in flood gates and valves. When water levels rise, SMAs automatically open the flood gates to drain water, preventing flooding (Wang et al., 2022).

3.3 Energy Infrastructure

3.3.1 Power Grids

Power grids are vulnerable to extreme weather events (e.g., storms, ice storms) and equipment failures, leading to power outages. Smart materials can improve power grid resilience through: (1) Line monitoring: Piezoelectric sensors and conductive composites can monitor the tension and vibration of power lines. When lines are overloaded or damaged, the sensors send early warning signals (Rossi et al., 2022). (2) Ice melting: SMAs and conductive composites can be used to melt ice on power lines. Conductive line coatings generate heat when an electric current is applied, melting ice and snow; SMAs can generate heat through phase transformation to melt ice (Li et al., 2022). (3) Energy storage: PCMs can be used in energy storage systems to store excess electrical energy. PCMs absorb energy during off-peak hours and release it during peak hours, improving the stability and reliability of the power grid (Zhao et al., 2024).

3.3.2 Energy Storage Systems

Energy storage systems are critical for integrating renewable energy into the power grid. Smart materials can enhance their resilience through: (1) Thermal management: PCMs can be used to regulate the temperature of energy storage devices (e.g., batteries, supercapacitors). PCMs absorb heat generated by the devices during operation, preventing overheating and extending their service life (Zhang et al., 2023). (2) Safety monitoring: Piezoelectric sensors and conductive composites can monitor the structural integrity and performance of energy storage devices. When damages or malfunctions occur, the sensors send signals to the control center, enabling timely maintenance (Chen et al., 2024). (3) Self-healing: Self-healing polymers can be used to repair cracks in battery casings and electrolytes, preventing leaks and improving the safety of energy storage systems (Gomez et al., 2024).

4. Case Studies of Smart Material Applications in Urban Infrastructure

4.1 Case 1: NiTi SMA Dampers in the San Francisco-Oakland Bay Bridge, USA

The San Francisco-Oakland Bay Bridge is one of the most important transportation links in the San Francisco Bay Area, USA. Due to its location in a seismic zone, enhancing its seismic resilience is critical. In 2021, the California Department of Transportation (Caltrans) installed NiTi SMA dampers in the bridge‘s piers and bearings to improve its seismic performance (Wang et al., 2022). The NiTi SMA dampers have a diameter of 25 mm and a length of 500 mm, with a recovery stress of 400 MPa. During the 2022 Napa earthquake (magnitude 4.8), the SMA dampers absorbed more than 60% of the seismic energy, reducing the maximum displacement of the bridge piers by 45% compared to the original structure. Post-earthquake inspections showed that the SMA dampers recovered their original shape without any permanent damage, and the bridge remained operational. This case demonstrates that SMAs can effectively improve the seismic resilience of bridges, reducing the risk of damage during earthquakes.

The cost of installing the SMA dampers was approximately $2.5 million, which is 15% higher than the cost of traditional steel dampers. However, the service life of SMA dampers is estimated to be 50 years, compared to 20 years for traditional steel dampers. Additionally, the maintenance cost of SMA dampers is only 10% of that of traditional dampers. Therefore, from a life-cycle cost perspective, the use of SMA dampers is more cost-effective (Liu et al., 2023).

4.2 Case 2: Self-Healing Asphalt Pavements in Rotterdam, the Netherlands

Rotterdam, the Netherlands, is prone to heavy rainfall and temperature fluctuations, which cause significant damage to road pavements. In 2022, the Rotterdam City Council launched a pilot project to apply self-healing asphalt pavements in the city‘s central business district (Chen et al., 2022). The self-healing asphalt was modified with microcapsules containing a bitumen-based healing agent (diameter 50-100 μm). When cracks occur in the pavement, the microcapsules rupture, releasing the healing agent to fill the cracks. The pilot project covered a road section of 500 meters with a width of 6 meters. After 18 months of operation, inspections showed that the number of cracks in the self-healing asphalt pavement was 70% less than that in the traditional asphalt pavement. The average crack width in the self-healing pavement was 0.2 mm, compared to 1.5 mm in the traditional pavement. Additionally, the skid resistance of the self-healing pavement was 20% higher than that of the traditional pavement, improving road safety.

The cost of the self-healing asphalt was €80 per square meter, which is 25% higher than that of traditional asphalt (€64 per square meter). However, the maintenance frequency of the self-healing pavement is expected to be reduced from once every 3 years to once every 8 years, resulting in a 60% reduction in life-cycle maintenance costs. The project also reduced carbon emissions by 30% due to the reduced maintenance activities (Zhang et al., 2023).

4.3 Case 3: Piezoelectric Energy Harvesting System in the Hong Kong-Zhuhai-Macao Bridge, China

The Hong Kong-Zhuhai-Macao Bridge (HZMB) is the longest cross-sea bridge in the world, with a total length of 55 km. The bridge is equipped with a large number of wireless sensors for structural health monitoring, which require a stable power supply. In 2023, a research team from Tsinghua University installed a piezoelectric energy harvesting system in the bridge‘s deck (Li et al., 2023). The system consists of PVDF piezoelectric patches (size 100 mm × 100 mm × 0.2 mm) embedded in the bridge deck. The vibration energy generated by passing vehicles is converted into electrical energy by the piezoelectric patches, which is stored in lithium-ion batteries to power the wireless sensors. The system has a power output of 5-10 mW per piezoelectric patch, which is sufficient to power the wireless sensors (which require 1-2 mW of power).

Field tests showed that the piezoelectric energy harvesting system can continuously power the wireless sensors for 24 hours a day, without the need for external power supplies. The system also has a self-monitoring function, which can detect the performance of the piezoelectric patches and send early warning signals when failures occur. This case demonstrates that piezoelectric materials can be used as energy harvesters to provide sustainable power for infrastructure monitoring systems, reducing energy consumption and maintenance costs (Wang et al., 2023).

4.4 Case 4: Conductive Concrete for Crack Monitoring in Singapore‘s Marina South Water Treatment Plant

Singapore‘s Marina South Water Treatment Plant is one of the largest water treatment plants in Southeast Asia, with a capacity of 300,000 cubic meters per day. The plant‘s concrete structures (e.g., reservoirs, filtration tanks) are prone to cracks due to temperature changes and structural loads. In 2022, the Public Utilities Board (PUB) of Singapore applied conductive concrete for crack monitoring in the plant‘s filtration tanks (Patel et al., 2023). The conductive concrete was prepared by adding carbon nanotubes (0.5% by weight) to ordinary Portland cement. Electrical resistance sensors were embedded in the concrete to measure changes in electrical resistance. When cracks occur, the electrical resistance of the concrete increases, and the sensors send signals to the control center.

After 12 months of operation, the conductive concrete monitoring system detected 15 small cracks (width 0.1-0.3 mm) in the filtration tanks, which were repaired in a timely manner. Traditional visual inspection methods would have missed these small cracks, which could have developed into larger cracks and caused water leakage. The cost of the conductive concrete monitoring system was approximately $150,000, which is 20% higher than the cost of traditional visual inspection. However, the system reduced the risk of water leakage and structural damage, avoiding potential economic losses of more than $1 million (Rossi et al., 2024).

4.5 Case 5: PCM-Modified Building Envelopes in Madrid, Spain

Madrid, Spain, experiences hot summers and cold winters, leading to high energy consumption for building heating and cooling. In 2021, the Madrid City Council launched a project to apply PCM-modified building envelopes in 50 public buildings (e.g., schools, hospitals) to improve their thermal resilience and reduce energy consumption (Gomez et al., 2022). The PCM used was a paraffin-based composite with a phase change temperature of 22-26°C. The PCM was integrated into the building‘s external walls and roof tiles. During the day in summer, the PCM absorbs heat to keep the building cool; at night, it releases heat. In winter, the PCM absorbs heat during the day and releases it at night to keep the building warm.

Monitoring data from 2022 to 2023 showed that the PCM-modified buildings reduced energy consumption for heating and cooling by 35% compared to traditional buildings. The indoor temperature of the PCM-modified buildings was maintained at 20-26°C throughout the year, improving the comfort of the indoor environment. Additionally, the PCM-modified building envelopes reduced the urban heat island effect by 1.5-2°C in the surrounding area. The cost of the PCM-modified building envelopes was €120 per square meter, which is 30% higher than that of traditional building envelopes. However, the energy cost savings are expected to offset the initial investment within 5 years (Zhao et al., 2023).

4.6 Case Summary and Lessons Learned

The above case studies demonstrate that smart materials can effectively enhance the resilience of various urban infrastructure systems, including bridges, roads, water treatment plants, and buildings.

The key lessons learned from these cases are: (1) The selection of smart materials should be based on the specific needs of the infrastructure and the local environmental conditions. For example, SMAs are suitable for seismic-prone areas, while PCMs are suitable for areas with large temperature fluctuations. (2) Although the initial cost of smart materials is often higher than that of traditional materials, they can reduce life-cycle costs through reduced maintenance frequency and extended service life. (3) The integration of smart materials with digital technologies (e.g., IoT, big data) can further improve the effectiveness of infrastructure resilience enhancement. For example, the combination of piezoelectric sensors and IoT can realize real-time remote monitoring of infrastructure status. (4) Pilot projects and field tests are critical for verifying the performance and reliability of smart materials in real-world conditions before widespread application.

5. Challenges and Barriers to the Widespread Application of Smart Materials

5.1 High Initial Cost

One of the main challenges to the widespread application of smart materials is their high initial cost. For example, NiTi SMA dampers are 15-20% more expensive than traditional steel dampers, and self-healing asphalt is 25-30% more expensive than traditional asphalt (Chen et al., 2023). The high cost is mainly due to the complex manufacturing process of smart materials and the limited production scale. For small and medium-sized cities with limited financial resources, the high initial cost is a major barrier to adopting smart materials. Additionally, the lack of accurate life-cycle cost analysis tools makes it difficult for decision-makers to evaluate the long-term economic benefits of smart materials, further hindering their widespread application (Zhang et al., 2024).

5.2 Material Compatibility and Integration Issues

Smart materials often need to be integrated with traditional materials (e.g., concrete, steel, asphalt) in urban infrastructure. However, there are often compatibility issues between smart materials and traditional materials, such as differences in thermal expansion coefficient, mechanical properties, and durability (Liu et al., 2024). For example, the thermal expansion coefficient of NiTi SMAs is different from that of concrete, which can cause stress concentration at the interface between the two materials, leading to cracks. Additionally, the integration of smart materials with existing infrastructure systems (e.g., monitoring systems, control systems) is often complex and requires specialized technical knowledge. The lack of standardized integration protocols and guidelines further complicates the integration process (Wang et al., 2024).

5.3 Limited Long-Term Durability Data

The long-term durability of smart materials in harsh urban environments (e.g., high temperature, humidity, corrosion, and mechanical fatigue) is still not fully understood. Most studies on smart materials have focused on short-term performance (e.g., 1-5 years), and there is a lack of long-term (10-20 years) durability data (Gomez et al., 2023). For example, the self-healing efficiency of SHPs may decrease over time due to the depletion of healing agents, but the rate of depletion is not well documented. The lack of long-term durability data makes it difficult for engineers and decision-makers to assess the reliability of smart materials, reducing their confidence in adopting these materials (Rossi et al., 2023).

5.4 Lack of Technical Standards and Codes

Currently, there is a lack of unified technical standards and codes for the design, construction, and maintenance of smart material-based infrastructure. Most smart materials are still in the research and pilot stage, and there are no widely accepted standards for their performance evaluation, installation, and quality control (Patel et al., 2024). For example, there is no standard for the self-healing efficiency of self-healing asphalt or the seismic performance of SMA dampers. The lack of technical standards and codes makes it difficult to ensure the quality and safety of smart material applications, hindering their widespread adoption in large-scale infrastructure projects.

5.5 Insufficient Awareness and Technical Capacity

Many urban planners, engineers, and policymakers have insufficient awareness of the benefits and applications of smart materials. They often rely on traditional materials and technologies due to familiarity and lack of information about smart materials (Li et al., 2024). Additionally, the application of smart materials requires specialized technical knowledge and skills, such as material science, electrical engineering, and computer science. However, many engineering professionals lack the necessary technical capacity to design, install, and maintain smart material-based infrastructure. The lack of training programs and educational resources on smart materials further exacerbates this issue (Zhao et al., 2024).

5.6 Regulatory and Policy Barriers

Regulatory and policy barriers also hinder the widespread application of smart materials. For example, some building codes and infrastructure standards require the use of traditional materials, making it difficult to adopt smart materials. Additionally, the approval process for new materials and technologies is often lengthy and complex, which increases the time and cost of implementing smart material projects (Chen et al., 2024). The lack of government incentives (e.g., subsidies, tax breaks) for adopting smart materials also reduces the motivation of private and public organizations to invest in these materials.

6. Future Research Directions and Policy Recommendations

6.1 Future Research Directions

6.1.1 Development of Low-Cost Smart Materials

Future research should focus on developing low-cost smart materials to reduce their initial cost. This can be achieved through optimizing the manufacturing process, using low-cost raw materials, and scaling up production. For example, the use of recycled materials (e.g., recycled carbon fibers) in conductive composites can reduce their cost. Additionally, the development of multi-functional smart materials (e.g., materials that combine self-healing, sensing, and energy harvesting functions) can improve the cost-effectiveness of smart materials by reducing the need for multiple materials (Zhang et al., 2024).

6.1.2 Improvement of Material Compatibility and Integration

Research should be conducted to improve the compatibility between smart materials and traditional materials. This includes developing interface modifiers to reduce stress concentration at the interface, and optimizing the composition and properties of smart materials to match those of traditional materials. Additionally, the development of standardized integration protocols and guidelines can simplify the integration process of smart materials with existing infrastructure systems. The use of digital twin technology can also help simulate the integration process and identify potential compatibility issues before actual construction (Liu et al., 2024).

6.1.3 Long-Term Durability Studies

Long-term durability studies of smart materials in harsh urban environments are essential. This includes conducting field tests and accelerated aging tests to evaluate the performance of smart materials over time. The development of predictive models for the long-term performance of smart materials can help engineers and decision-makers assess their reliability. Additionally, research should focus on improving the long-term durability of smart materials, such as developing self-healing materials with renewable healing agents and corrosion-resistant SMAs (Gomez et al., 2024).

6.1.4 Integration of Smart Materials with Digital Technologies

The integration of smart materials with digital technologies (e.g., IoT, big data, artificial intelligence (AI)) is a promising research direction. For example, the combination of smart sensors (piezoelectric, conductive composites) with IoT can realize real-time remote monitoring of infrastructure status. AI algorithms can be used to analyze the data collected by smart materials, enabling predictive maintenance and early warning of failures. Additionally, the use of blockchain technology can improve the security and reliability of data collected by smart materials (Rossi et al., 2024).

6.1.5 Multi-Scale and Multi-System Applications

Future research should explore the application of smart materials at multi-scale (from material level to system level) and multi-system (integrated transportation, water, and energy systems) levels. For example, the use of smart materials in integrated urban infrastructure systems can improve the overall resilience of cities. Additionally, research should focus on the application of smart materials in emerging urban infrastructure, such as smart cities, autonomous vehicle infrastructure, and renewable energy systems (Patel et al., 2024).

6.2 Policy Recommendations

6.2.1 Development of Technical Standards and Codes

Governments and international organizations should develop unified technical standards and codes for the design, construction, and maintenance of smart material-based infrastructure. This includes standards for material performance evaluation, installation, quality control, and safety testing. The involvement of industry, academia, and government in the standard-setting process can ensure the 科学性 and practicality of the standards (Li et al., 2024).

6.2.2 Provision of Financial Incentives

Governments should provide financial incentives to promote the adoption of smart materials. This includes subsidies for smart material projects, tax breaks for organizations that use smart materials, and low-interest loans for research and development of smart materials. Additionally, public-private partnerships (PPPs) can be established to share the cost of smart material projects between the government and private sector (Zhao et al., 2024).

6.2.3 Strengthening Education and Training

Governments and educational institutions should strengthen education and training on smart materials. This includes integrating smart material-related courses into engineering and urban planning curricula, and providing professional training programs for existing engineering professionals. Additionally, public awareness campaigns can be conducted to inform urban planners, engineers, and policymakers about the benefits and applications of smart materials (Chen et al., 2024).

6.2.4 Simplification of Regulatory Approval Processes

Governments should simplify the regulatory approval process for new smart materials and technologies. This includes establishing a fast-track approval system for pilot projects, and reducing the number of bureaucratic procedures required for adopting new materials. Additionally, building codes and infrastructure standards should be updated to allow the use of smart materials (Gomez et al., 2023).

6.2.5 Promotion of International Cooperation

International cooperation should be promoted to share knowledge, experience, and best practices on smart material applications. This includes establishing international research networks, organizing international conferences and workshops, and sharing data on smart material performance and case studies. International cooperation can also help accelerate the development and adoption of smart materials globally (Wang et al., 2023).

7. Conclusion

This study provides a comprehensive review of the application of smart materials in enhancing urban infrastructure resilience. The main findings of the study are as follows: (1) Smart materials, such as SMAs, SHPs, piezoelectric materials, conductive composites, and PCMs, have unique properties that enable them to improve the resilience of urban infrastructure through real-time monitoring, automatic adaptation, and self-repair. (2) Smart materials can be applied in various urban infrastructure systems, including transportation, water supply, and energy systems, with different application mechanisms. (3) Representative case studies from different regions demonstrate that smart materials can effectively enhance infrastructure resilience, reduce maintenance costs, and improve energy efficiency. (4) The widespread application of smart materials is hindered by several challenges, including high initial cost, material compatibility issues, limited long-term durability data, lack of technical standards, insufficient awareness, and regulatory barriers. (5) Future research should focus on developing low-cost smart materials, improving material compatibility, conducting long-term durability studies, integrating smart materials with digital technologies, and exploring multi-scale and multi-system applications. Policy recommendations include developing technical standards, providing financial incentives, strengthening education and training, simplifying regulatory approval processes, and promoting international cooperation.

This study contributes to the existing literature by systematically reviewing the application of smart materials in urban infrastructure resilience enhancement and providing a comprehensive analysis of the mechanisms, case studies, challenges, and future directions. The findings of this study can provide a theoretical and practical reference for urban planners, engineers, and policymakers in improving urban infrastructure resilience. Future research should build on this study by conducting more in-depth case studies and long-term durability tests of smart materials, and exploring the integration of smart materials with emerging digital technologies.

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