

Research Paper

Received: 29 September 2025, Accepted: 06 January 2026, Published online: 31 January 2026

**DOI: 10.21625/archive-sr.v10i1.1243**

# **The Role of Smart Materials in Future Architecture: Self-Healing, Adaptive, and Sustainable Innovation**

**Aida Al Hosni<sup>1</sup>***<sup>1</sup>PhD student in the architectural department at Ion Mincu University of Architecture and Urbanism, Bucharest, Romania*

---

## **Abstract**

The integration of smart materials into architecture is redefining the built environment by introducing innovations that are self-healing, adaptive, and sustainable. (Nicolay et al., 2021a; Wang et al., 2025) These advanced materials react dynamically to external stimuli such as temperature, humidity, and stress, improving resilience, energy efficiency, and user comfort. Among the most significant examples are self-healing concrete and thermochromic glass, which enable buildings to repair minor damage and adapt to changing climate conditions. The implications of these materials extend beyond single structures, influencing urban planning and sustainable development strategies aimed at creating resilient, energy-efficient cities.

Self-healing concrete, developed through bacterial processes at Delft University of Technology, exemplifies how biological mechanisms can extend structural lifespan and reduce maintenance costs. Likewise, thermochromic glass, featured in projects such as The Edge in Amsterdam, regulates light and heat transfer, reducing dependence on artificial systems. These technologies represent the shift from static to dynamic architecture capable of real-time environmental interaction. (Jonkers & Schlangen, 2008; Garshasbi & Santamouris, 2019)

However, the adoption of smart materials faces challenges, including cost, durability verification, and limited awareness in professional education. This paper analyzes key categories of smart materials, case studies of self-healing and adaptive technologies, and their broader implications for sustainable design and urban planning. It also introduces the need for specialized academic coursework integrating materials science and architecture to equip future designers with the knowledge required for sustainable innovation. Ultimately, smart materials pave the way toward cities that are not only efficient but also regenerative and responsive to their environments.

© 2026 The Authors. Published by IEREK Press. This is an open-access article under the CC BY license (<https://creativecommons.org/licenses/by/4.0/>). Peer review under the responsibility of ARChive-SR's International Scientific Committee of Reviewers.

## **Keywords**

*Specialized coursework, Architectural change, Sustainable city, smart material, urban development*

---

## **1. Introduction**

Architecture is stepping into an exciting new phase, one that goes beyond just how buildings look or function. Today, architects and engineers are embracing smart materials—innovative substances that can react in real-time to their environment—to tackle pressing issues like climate change, urban growth, and resource limitations. These materials are designed to adjust to factors like temperature, humidity, light, or mechanical stress, which makes buildings not only more energy-efficient but also more resilient and sustainable. (Addington & Schodek, 2012; Barbhuiya, 2025)

Take self-healing concrete, for example. It's infused with bacteria that spring into action when exposed to water and air, sealing cracks with a natural mineral called calcite. Then there's thermochromic glass, which automatically tints itself based on how intense the sunlight is, helping regulate indoor temperatures without relying on mechanical systems. A great illustration of these concepts in action is The Edge in Amsterdam, widely regarded as one of the greenest office buildings in the world—an example of how smart materials can create energy-efficient, intelligent spaces. Other promising innovations include phase change materials (PCMs) that manage heat for comfort, and shape-memory alloys that can return to a set shape when conditions change, which can be used in responsive building facades. (Shafa, 2024)

As these materials become more readily available and developed, they're not just enhancing how individual buildings perform; they're reshaping how we think about designing cities for the future, sustainability, and ecological resilience. This article looks at the role of smart materials in future architecture, focusing on their self-healing, adaptive, and sustainable qualities. It also explores how these innovations could change both structural design and urban planning, signaling a broader transformation in education and professional practices within architecture.

However, despite their potential, smart materials face barriers to widespread adoption, including high costs, limited familiarity among practitioners, and the absence of dedicated academic training (Szolomicki, 2020). Addressing these limitations requires integrating materials science into architectural curricula and fostering collaboration across disciplines. This article explores the types, mechanisms, and applications of smart materials—particularly self-healing and adaptive variants—and discusses their role in shaping sustainable architectural and educational practices for the future.

## 2. Methodology

The research adopts a qualitative and analytical approach based on an integrative literature review and comparative case study analysis. The goal is to synthesize existing research and practical examples to evaluate how smart materials contribute to sustainability, adaptability, and resilience in architectural design.

The research integrates several approaches, including a documentary analysis of academic journals, technical reports, and case studies released from 2015 to 2025. It also features a comparative assessment of notable examples like self-healing concrete from TU Delft and thermochromic glass utilized in The Edge, Amsterdam. Additionally, the study reviews educational frameworks that encourage material innovation in architecture. Data were sourced from peer-reviewed databases such as Scopus, ScienceDirect, and SpringerLink, utilizing keywords related to smart materials in architecture, self-healing concrete, adaptive façades, and thermochromic glass.

Studies were selected if they:

- Addressed architectural applications of smart materials;
- Included empirical or pilot data on performance metrics (e.g., durability, energy efficiency, CO<sub>2</sub> reduction);
- Papers focusing exclusively on mechanical engineering or unrelated nanomaterial studies were excluded unless directly relevant to architectural contexts.

The analysis is structured around three main dimensions: First, it explores the functional mechanisms of smart materials, focusing on their reactions to environmental stimuli, such as self-healing properties and thermochromic or electrochromic responses. Second, it assesses how these materials integrate into architectural design, impacting energy management and enhancing urban resilience. Finally, it addresses the educational and policy implications, highlighting the importance of knowledge transfer and curriculum development in fostering a sustainable adoption of these innovative materials.

The two main case studies—TU Delft's bacterial concrete and The Edge in Amsterdam—were chosen for their exemplary representation of biological and adaptive material innovation in architectural practice. Both projects have been widely cited for their technological and environmental impact (Wiktor & Jonkers, 2011; BREEAM, 2015).

The research design and analytical framework adopted in this study are illustrated in Figure 1.

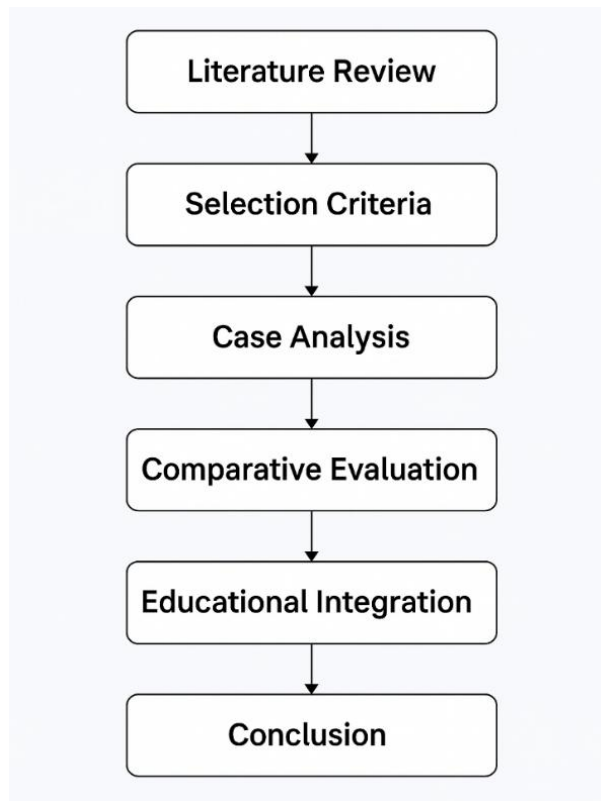


Figure 1: Research Design and Analysis Flowchart

This structured approach ensures academic rigor and provides a reproducible framework for future studies on smart material integration in sustainable architecture.

### 3. Understanding Smart Materials

In the pursuit of sustainability and resilience, smart materials have emerged as a transformative force in contemporary architecture. Unlike traditional materials, which remain static throughout their lifespan, smart materials exhibit responsiveness, adaptability, and multifunctionality—enabling buildings to interact intelligently with their surroundings (Nicolay et al., 2021a). Their ability to detect and respond to environmental stimuli such as light, temperature, humidity, or mechanical stress allows for structures that self-adjust to maintain optimal comfort, efficiency, and performance.

Recent research suggests that buildings incorporating smart materials can reduce operational energy demand by 20–45%, extend material life cycles by 30–50%, and lower maintenance costs by up to 40% (Konarzewska, 2017; Sun et al., 2022). This makes them essential for achieving climate-responsive and energy-efficient architectural solutions.

Examples like self-healing concrete, which uses embedded bacteria to seal cracks automatically, or thermochromic glass that darkens in response to sunlight, illustrate how these materials are transforming the design approach for architects and engineers. Additionally, phase-change materials that can store and release heat and shape-memory alloys that revert to a predetermined shape highlight the range and adaptability of smart materials.

To understand smart materials better, it's important to consider their basic principles, the types of stimuli they respond to, and the advantages they offer compared to conventional materials. This chapter will delve into their definitions, classifications, and practical applications, setting the stage for how they can influence not just individual buildings but the urban landscapes of the future.

#### 1. Definition & Classification of Smart Materials:

Smart materials are substances engineered to alter one or more of their physical properties—such as shape, color, stiffness, or electrical conductivity—when exposed to external stimuli (Ashby et al., 2013). They can be broadly categorized into two main groups:

- **Stimulus-Responsive Property-Changers:** Shape-memory alloys (SMAs) and shape-memory polymers (SMPs) are materials that can alter their shape when subjected to specific triggers, such as temperature changes or mechanical stress. Similarly, phase-change materials (PCMs) function like thermal batteries, capable of absorbing and releasing heat by transitioning between solid and liquid states. Additionally, chromogenic materials are designed to change their appearance—whether through opacity or color—when exposed to various stimuli. This category includes types like electrochromic, thermochromic, and photochromic materials.
- **Energy-Transforming Materials:** Photovoltaic materials can convert light into electrical energy, making them essential for solar technologies. On the other hand, piezoelectric materials can generate electrical energy when mechanically deformed, and they can also function the opposite way, converting electrical energy into mechanical motion.

Some notable examples are Self-Healing Concrete (Bioconcrete), this innovative material incorporates *Bacillus* bacteria, which remain inactive until cracks form. Once moisture penetrates the cracks, the bacteria become active and begin to produce calcium carbonate, effectively sealing the gaps.

Self-healing concrete is utilized in various structures, including bridges, tunnels, and buildings, to improve longevity and minimize maintenance needs. Notable projects featuring this technology include art museums in Rio de Janeiro, along with other essential infrastructure.

Another one will be Electrochromic (Smart) Glass, this type of glass has the ability to adjust its tint or opacity in response to an electric signal. This feature helps manage light, glare, temperature, and privacy effectively.

Smart glass is found in a variety of settings, such as on high-performance facades, including The Edge in Amsterdam, recognized as one of the most sustainable office buildings, where it aids in optimizing daylight and enhancing thermal comfort. It's also employed in elevators, train windows, and even bathrooms in Amsterdam, where it can switch from transparent to opaque, ensuring privacy when needed.

## 2. Key characteristics of smart materials: responsiveness, adaptability, and multifunctionality:

Smart materials are different from traditional building materials because they can detect and respond to changes in their environment, and in some cases, they can even repair themselves. Their significance in architecture and urban planning is rooted in three key traits:

- **Responsiveness:** The ability of a material to detect and respond to specific environmental stimuli, such as temperature, light, pressure, or humidity, is known as environmental responsiveness. This responsiveness is achieved through embedded microstructures, chemical agents, or electronic components that trigger changes in the material's properties—such as color, shape, opacity, or structural integrity—when the environmental conditions change. For example, thermochromic glass used in buildings like The Edge in Amsterdam automatically adjusts its tint in response to sunlight. This feature helps control glare and reduce heat gain without the need for mechanical blinds or excessive air conditioning.
- **Adaptability:** Adaptive materials adjust to long-term environmental changes, often with memory functions that enhance performance over time. Self-healing concrete exemplifies this: bacterial agents activate upon crack formation, autonomously producing calcium carbonate that seals fissures. Studies at TU Delft revealed that this technology extends structural lifespan by 30–40% and lowers life-cycle maintenance costs by up to 50% (Wiktor & Jonkers, 2011; Basilisk, 2020).
- **Multifunctionality:** Smart materials perform multiple roles simultaneously—structural, environmental, and aesthetic. For example, PCM wall panels both store energy and regulate temperature, achieving 15–25% energy savings annually (Sun et al., 2022). Similarly, SMA-based shading devices combine dynamic movement with architectural expression, offering both mechanical function and design value.

Smart materials are proactive, integrated solutions rather than merely reactive novelties. Their responsiveness facilitates timely interaction with the environment, adaptability ensures long-term resilience, and multifunctionality maximizes both space and resource efficiency.

### 3. Role of smart materials in environmental interaction and real-time adaptation:

Modern architecture has evolved beyond static forms and passive designs. Buildings are now expected to actively interact with their surroundings, responding to environmental factors in ways that enhance efficiency, comfort, and resilience. At the forefront of this transformation are smart materials, which allow structures to become dynamic participants in their environment rather than merely inert objects.

Smart materials have the capacity to detect, process, and respond to external environmental cues such as temperature, sunlight, wind, humidity, and pollution. In architecture, incorporating smart materials into building skins, facades, and interiors allows architects to create structures that function as sensory systems.

Electrochromic and thermochromic glass can adjust their transparency in response to light and heat, helping to reduce energy consumption for lighting and cooling. Hydroceramic panels, which are made of clay and hydrogel, absorb moisture from the air and cool indoor spaces through evaporation. They naturally respond to changes in humidity and temperature. This approach minimizes reliance on mechanical systems, reduces energy consumption, and promotes passive climate control.

Real-time adaptation refers to a material's ability to change its physical or functional characteristics immediately in response to shifting environmental conditions. In the field of architecture, this capability allows structures to enhance their performance at any given time. This could involve adjustments in thermal insulation, modifications to light penetration, or the proactive repair of micro-damage before it has a chance to develop further. (Ashby et al., 2013; Kumar & Suresh, 2025)

An example of this is self-healing concrete, which activates its crack-sealing mechanism in response to damage and the presence of moisture. This innovative material helps maintain the structural integrity of buildings promptly, preventing further deterioration without unnecessary delays. Also, phase-change materials (PCMs) embedded in building walls play a crucial role in managing heat. During the day, they absorb excess heat and release it at night, promoting thermal stability throughout the daily temperature fluctuations. The interaction mechanisms of smart materials within the built environment are illustrated in Figure 2.

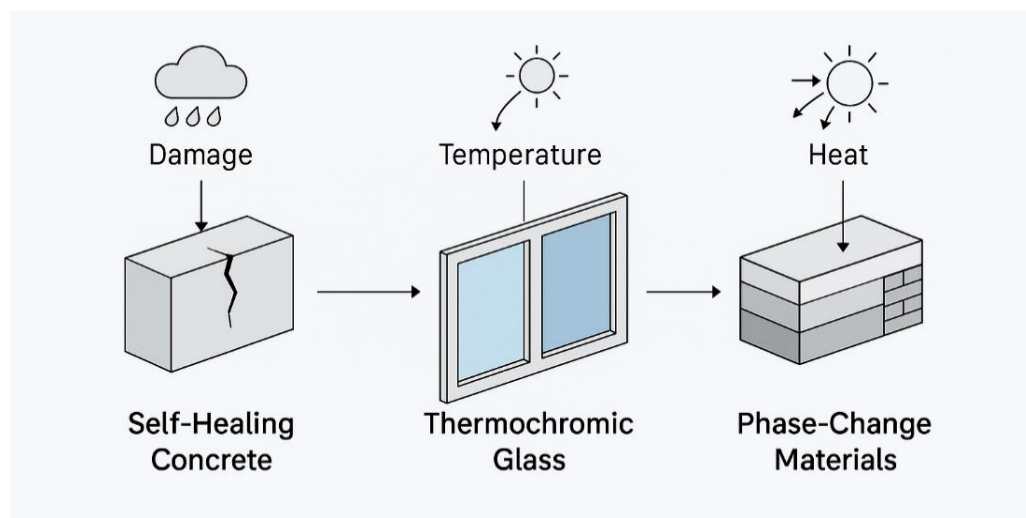


Figure 2: Interaction Mechanisms of Smart Materials in Architecture

The integration of environmental interaction with real-time adaptation enables buildings to function similarly to living organisms. These structures are designed to monitor their environments, respond immediately to changes, and evolve to enhance their long-term performance.

These adaptive mechanisms redefine the architectural envelope as a performative interface—an intelligent skin that regulates energy flow, mitigates environmental stress, and enhances user experience. This integration not only optimizes building performance but also contributes to long-term sustainability metrics, aligning with carbon-neutral design strategies and climate adaptation goals.

In terms of urban planning, this approach translates into cities that have infrastructures equipped to effectively address various challenges. These include alleviating the urban heat island effect, managing sudden weather events without sustaining structural damage, and dynamically reducing energy demand across entire districts.

The function of smart materials is not just practical; it is transformative. By connecting static architecture with responsive systems, they pave the way for climate-adaptive, self-sustaining buildings that actively contribute to environmental balance.

### **3.1. Self-Healing Materials in Architecture.**

In conventional construction, damage to materials—stemming from environmental factors, mechanical forces, or natural wear and tear—results in expensive repairs, more frequent maintenance, and reduced lifespan of buildings. Self-healing materials represent a significant shift from this reactive approach by allowing structures to automatically mend themselves, similar to how biological systems heal injuries. These innovative materials incorporate embedded agents like microcapsules, polymers, or even live bacteria that get activated upon sustaining damage, effectively restoring the structural integrity without the need for human assistance.

One prominent example in architecture is self-healing concrete, which can autonomously seal cracks when it comes into contact with moisture and oxygen. By using such materials in building elements, architects can greatly prolong the lifespan of structures, decrease long-term maintenance expenses, and lessen the environmental impact by reducing the need for repairs and replacements.

The advantages of self-healing materials extend beyond just economic benefits. They improve structural resilience against weather conditions, earthquakes, and other pressures; promote sustainable development by curtailing waste and emissions; and enable innovative design techniques that focus on durability and flexibility. As urban areas face heightened challenges from climate change and population increases, self-healing technologies emerge as a vital advancement for building cities that are not only intelligent but also sustainable over time.

Self-healing materials draw inspiration from biological systems—similar to how skin repairs itself after an injury. These materials are engineered to identify damage and trigger a self-repair process without any human involvement. In the field of architecture, they primarily aim to enhance the durability of structural elements, uphold safety standards, and reduce the necessity for expensive and resource-heavy maintenance.

Although self-healing technology can be utilized in metals, polymers, and composites, its most groundbreaking application in construction has been in concrete, which often develops cracks over time due to environmental pressures, load cycles, and temperature changes.

The self-healing process in materials is fascinating and depends on the type of material and the repair agents used within it. It all begins when damage is detected. Microcracks can form in a material due to various factors like stress, temperature changes, or simply the aging of the material. These tiny cracks create openings for moisture and oxygen to seep in, which can worsen the situation if left unattended.

Once damage is detected, the next step is activating the healing agent. For instance, in an innovative concept called “bioconcrete” developed at Delft University, the concrete contains *Bacillus* bacteria spores along with a nutrient source like calcium lactate. When water enters a crack, it triggers the bacteria to germinate and consume the nutrients. This process produces calcium carbonate, or limestone, which then fills and seals the crack, effectively mending the material. Similarly, in polymer-based self-healing materials, there are microcapsules filled with liquid resin embedded in the polymer. When a crack occurs, it ruptures these microcapsules, releasing the resin to flow into the crack and solidify, restoring the material’s strength. Shape-memory alloys and composites work a bit differently; applying heat or stress causes a rearrangement at the molecular level that closes the crack.

The self-healing mechanism of bacterial concrete is illustrated in Figure 3.

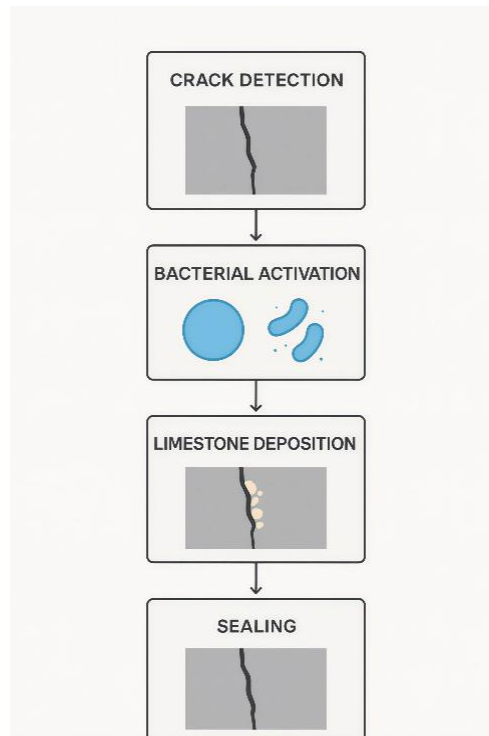


Figure 3: The working process of the self-healing concrete

The final step is restoration, which is crucial for recovering the material's integrity. When these cracks are filled, it helps prevent further damage and significantly reduces the risk of structural failure. In some cases, the area that has healed can actually match or even exceed the strength of the original material, showcasing just how remarkable these self-healing processes can be.

Architects and the field of architecture can make great use of this versatile material in various projects due to its numerous advantages. One of the standout features is its structural durability, which helps stop small cracks from becoming serious issues. This is particularly important for maintaining the integrity and safety of buildings and other structures over time.

Beyond just durability, this material plays a significant role in promoting sustainability. Reducing the need for regular repairs and replacements, it helps lower the carbon footprint associated with construction. This not only benefits the environment but also encourages a more responsible approach to building.

Cost efficiency is another major benefit. Using this material can lead to significant savings in the long run, especially for large infrastructure projects like bridges, tunnels, and high-rise buildings. This makes it an appealing option for developers looking to manage budgets effectively without sacrificing quality. Safety is always a top priority in construction, especially when it comes to critical infrastructure. This material helps ensure that structures maintain their load-bearing capacity over time, offering peace of mind that they can endure the stresses of usage and the elements. Overall, its combination of durability, sustainability, cost efficiency, and safety makes it an excellent choice for a wide range of architectural projects.

### 3.2. Biological and chemical processes involved

Self-healing in concrete often utilizes a process known as microbially induced calcium carbonate precipitation (MICP). Here's how it functions: Dormant bacteria, primarily of the *Bacillus* family such as *Bacillus subtilis*, *Bacillus megaterium*, or *Sporosarcina pasteurii*, are incorporated into the concrete. This can be achieved by embedding them directly, through encapsulation, or by mixing them with lightweight aggregates.

When small cracks develop, moisture infiltrates the concrete and activates the bacterial spores, initiating their metabolic processes. The activated bacteria produce the enzyme urease, which facilitates the conversion of urea into ammonia and carbonates, resulting in an increase in the local pH.

This rise in pH encourages the formation of calcium carbonate ( $\text{CaCO}_3$ ), which creates crystalline deposits that fill and seal the cracks. Additionally, the bacterial cells, which carry a negative charge, serve as effective nucleation sites that attract calcium ions, aiding in mineral formation.

This ongoing cycle of detecting damage, activating bacteria, and precipitating calcite helps to restore the structural integrity of the concrete and can continue to function as new cracks appear, enhancing long-term durability.

Biological agents are increasingly being recognized for their potential to enhance longevity in various applications, particularly through the use of specific bacterial strains. Some commonly utilized strains include *Bacillus subtilis*, *Bacillus megaterium*, and *Sporosarcina pasteurii* (formerly known as *Bacillus pasteurii*). These strains have been optimized for their ability to thrive in alkaline environments and for their extended lifespan. A comparative life-cycle cost and carbon emission assessment is presented in Figure 4.

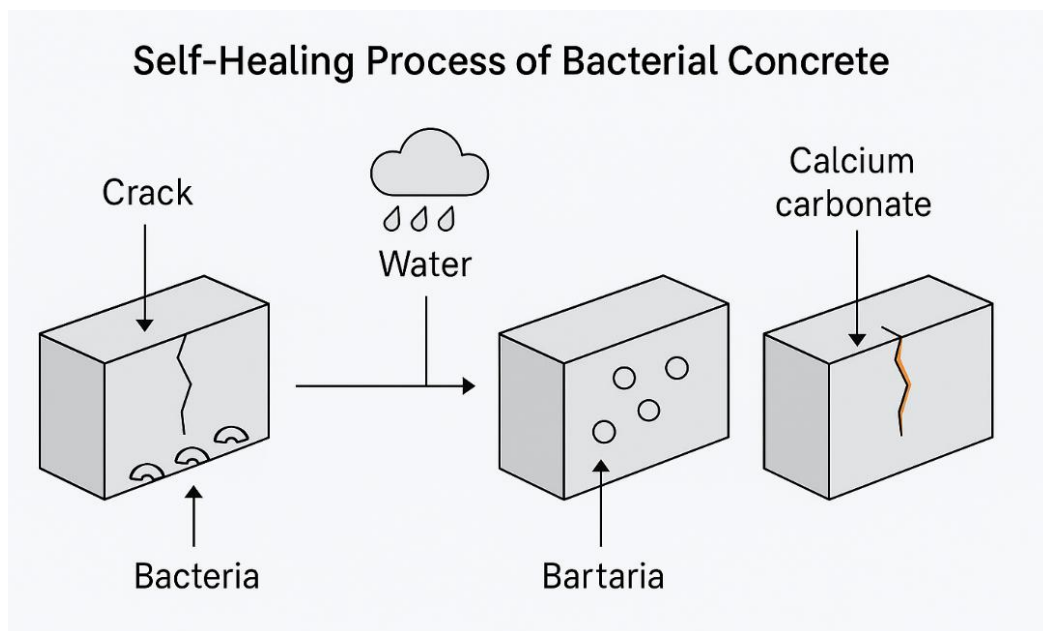


Figure 4: Self-Healing Process of Bacterial Concrete inspired by Jakhрани et al., 2019; Basilisk 2020

One of the remarkable features of these bacterial strains is their survivability. They can exist in a dormant spore form for decades or even centuries. This resilience allows them to withstand extreme conditions, such as high pH levels and desiccation, making them excellent candidates for long-lasting applications.

In laboratory studies, these bacteria have demonstrated impressive results. Research has shown that they can effectively seal cracks up to approximately 400 micrometers in width within just a few weeks. Additionally, the use of these biological agents has been linked to improvements in overall structural strength, reduced permeability, and enhanced durability.

In real-world scenarios, companies like Basilisk have successfully applied these biological methods in projects such as the “Sensicrete” and “Liquid Repair System ER7.” For instance, they have extended the lifespan of infrastructure like bus lanes at Schiphol Airport. These applications not only lead to significant reductions in life-cycle costs—around 33%—but also result in substantial savings in  $\text{CO}_2$  emissions, estimated at about 90%. Furthermore, these solutions offer at least a 15-year extension to the design life of the structures they enhance. (Basilisk BV, 2020; TU Delft, 2021)

#### 4. Case Study of a Self-Healing Concrete: Delft University of Technology’s bacterial concrete

Delft University of Technology (TU Delft) has been pioneering the development of a remarkable material known as bacterial self-healing concrete, or “bio-concrete.” This innovative concrete can repair its own cracks naturally through microbiological processes. The journey began in 2006 when TU Delft started research projects aimed at designing concrete with built-in self-repair capabilities. One of their key breakthroughs was mixing bacterial spores and lactate

into the concrete, which allows it to produce calcite that fills in any cracks. The idea was first shared at the First International Conference on Self-Healing Materials in 2007. During the research, they encountered the challenge of keeping the bacteria alive within the cement paste. To tackle this issue, they developed protective methods, like using expanded clay particles or glass capsules, to safely house the bacteria and ensure they could thrive.

Dormant bacterial spores embedded in the material become active when exposed to moisture, such as from micro-cracks. They then metabolize added organic nutrients like calcium lactate, leading to the formation of calcium carbonate (calcite), which effectively seals the crack and restores the material's structural integrity. Laboratory experiments have shown successful healing of micro-cracks up to approximately 0.15 mm wide, and tests on permeability have verified the restoration of the material's tightness.

A study conducted by Mors and Jonkers has documented full-scale demonstration projects utilizing this self-healing concrete over a span of more than ten years. Their findings indicate that cracks as wide as 0.8 mm can be completely.



Figure 5: Delft University of Technology

Healed under controlled laboratory environments, suggesting that it may be possible to decrease the amount of steel reinforcement needed in watertight constructions. This could lead to cost savings, lower CO<sub>2</sub> emissions, and more straightforward casting processes.

Although demonstrations in real-world conditions indicated that incorporating the healing agent did not negatively impact construction performance, the anticipated occurrence of cracks was less frequent than expected, resulting in limited definitive performance data. Nevertheless, ongoing initiatives aim to minimize reinforcement to better highlight the healing capabilities of the material.

TU Delft spin-off Green Basilisk (Delft University of Technology, 2006), shown in Figure 5, has successfully developed a technology to combat infrastructure decay, known as “concrete rot,” by incorporating bacteria spores into concrete. When activated by moisture, these bacteria generate limestone that fills in cracks, which helps minimize maintenance needs. This bio-concrete enables a 30–40% reduction in the amount of steel reinforcement required for new structures, leading to significant cost savings and environmental advantages. It can also be applied as a repair mortar to strengthen existing infrastructure and extend its lifespan.

This example highlights how the fusion of biology and materials science can transform construction methods, promoting a future of durable, low-maintenance, and environmentally friendly buildings. The team at TU Delft, led by Dr. Henk Jonkers and Renée Mors, has been dedicated to validating bacterial self-healing concrete (BSHC) beyond laboratory settings, focusing on real-world applications. Their demonstrator projects are crucial for complying with structural codes, such as Eurocode, which necessitate substantial evidence of safety and performance before a material can be commercially used.

In their efforts, they have implemented two main types of demonstrator projects. The first involves repair mortar demonstrators that have been applied to existing structures to test the effectiveness of healable patches. The second type consists of new concrete constructions, where BSHC has been utilized to assess its performance in practical scenarios. Initial findings from these projects reveal that incorporating the bacterial healing agent does not adversely affect the workability or structural integrity of the concrete. This compatibility with conventional construction methods is promising. However, an unexpected result has been the lower frequency of cracking, which has made it difficult to evaluate the healing performance effectively. Consequently, evidence for the effectiveness of crack-sealing in real-world conditions has been somewhat limited.

Looking ahead, the researchers are planning the next steps with a focus on a reinforcement-reduced design strategy. By deliberately decreasing crack-limiting reinforcement, they aim to create situations that induce measurable cracks, thus facilitating a clearer observation and quantification of the healing capabilities of BSHC. A specific project in this direction involves designing a rectangular watertight water reservoir as a test case. Simulations have predicted a range of crack widths, from about 0.09 mm to 0.43 mm, based on different reinforcement layouts, which will serve as targeted test points to assess the material's healing efficacy.

Demonstrators play a crucial role in proving that new technologies can really work, especially when it comes to the construction industry. They provide essential evidence to regulatory bodies about the benefits of these innovations, such as lower maintenance costs and improved sustainability. By showing how these technologies can be implemented effectively, demonstrators help to encourage wider acceptance and use in the field.

One of the exciting findings from lab tests is that self-healing materials can repair cracks of up to 0.8 mm. This opens the door to reducing the amount of reinforcement needed in structures, which could significantly lower carbon dioxide emissions and extend the life of buildings. It's a promising development that aligns with our growing emphasis on sustainable practices in construction.

By intentionally creating controlled cracking in specially designed structures, researchers can gather valuable data on how well these self-healing technologies perform. This information will be vital for shaping future design standards and practices, making it easier for engineers and architects to incorporate these innovations.

Overall, the work being done by TU Delft and others in this area is paving the way for a new era of architecture that prioritizes resilience and sustainability. The real-world testing of self-healing technology is an important step towards a construction industry that is not only more efficient but also friendlier to the environment.

Self-healing concrete brings many important benefits to building design and maintenance. This innovative material has the ability to repair itself, which enhances the lifespan of structures and saves money in the long run. One of the most significant advantages is that it helps buildings last longer. By preventing small cracks from growing into larger ones, self-healing concrete keeps structures stable for many more years than traditional concrete. The healing agents within the material can seal tiny cracks before water or harmful substances get inside, reducing issues related to freezing, corrosion, and chemical damage. As a result, this prolongs the life of the concrete itself, leading to a lower need for new materials and contributing to reduced carbon dioxide emissions from cement production. For example, researchers at Delft University of Technology developed a type of bacterial concrete that can heal cracks up to 0.8 mm wide, which significantly reduces wear over time.

Cost savings are another big benefit of using self-healing concrete. Traditional concrete requires regular maintenance, which can be time-consuming and expensive. With self-healing concrete, the frequency of repairs is significantly reduced. While the initial investment may be 20 to 50% higher compared to regular concrete, studies indicate that total costs can drop by up to 50% over a service life of 30 to 50 years because of less ongoing maintenance. Additionally, buildings made from self-healing concrete may have lower insurance costs due to their increased durability.

Field applications by Basilisk Self-Healing Concrete at Schiphol Airport and Dutch infrastructure projects revealed tangible benefits:

- Life-cycle cost reduction:  $\approx 33\%$

- CO<sub>2</sub> emissions reduction: ≈ 90% compared with conventional repair cycles
- Service-life extension: ≈ 30–40 years

Maintenance cost savings: ≈ 50% over a 50-year horizon (Basilisk BV, 2020).

Another advantage is that maintenance becomes much easier. This type of concrete can fix itself, which means less manual checking and fewer repairs are necessary. Buildings and infrastructure can continue to function while the concrete heals, avoiding costly downtime. For public infrastructure—like bridges and tunnels—this reduced maintenance allows for better use of resources elsewhere. A prime example of this is Basilisk Self-Healing Concrete, which has successfully been used in parking structures and marine environments, showing a significant reduction in maintenance needs.

#### 1. Broader Architectural Implications:

The incorporation of self-healing concrete into construction practices holds the promise of transforming the approach architects, engineers, and urban planners take towards designing and maintaining buildings. This innovative material’s flexibility and durability make it particularly suitable for structures that face significant stress and demand long-lasting solutions that also maintain cost-effectiveness.

In terms of application, self-healing concrete finds itself highly beneficial in foundations, bridges, and other high-demand structures. For foundations, which are often susceptible to water damage and soil pressure leading to cracks, self-healing properties can effectively prevent small cracks from worsening, ultimately reducing the necessity for expensive waterproofing solutions. Bridges also benefit greatly from this material, as they endure extreme weather conditions, heavy loads, and continual vibrations that make them prone to damage. The capability of self-healing concrete to seal minor cracks early on enhances safety and functionality, thereby lessening traffic disruptions during maintenance work. High-stress structures such as skyscrapers, dams, marine piers, and tunnel linings also reap the advantages of this technology, particularly in locations where access for routine inspection and upkeep can be challenging or risky.

Looking at the overall impact on life-cycle costs and structural integrity, although the upfront expense for using self-healing concrete may be elevated, it can lead to significant savings on repairs, downtime, and replacements over an extended service life that can exceed 50 years. Research shows that these savings could reach as much as 30 to 50% compared to conventional construction materials. Furthermore, by preventing crack growth from the onset, self-healing systems help to maintain the structural load capacity and safety factors throughout the life of the infrastructure.

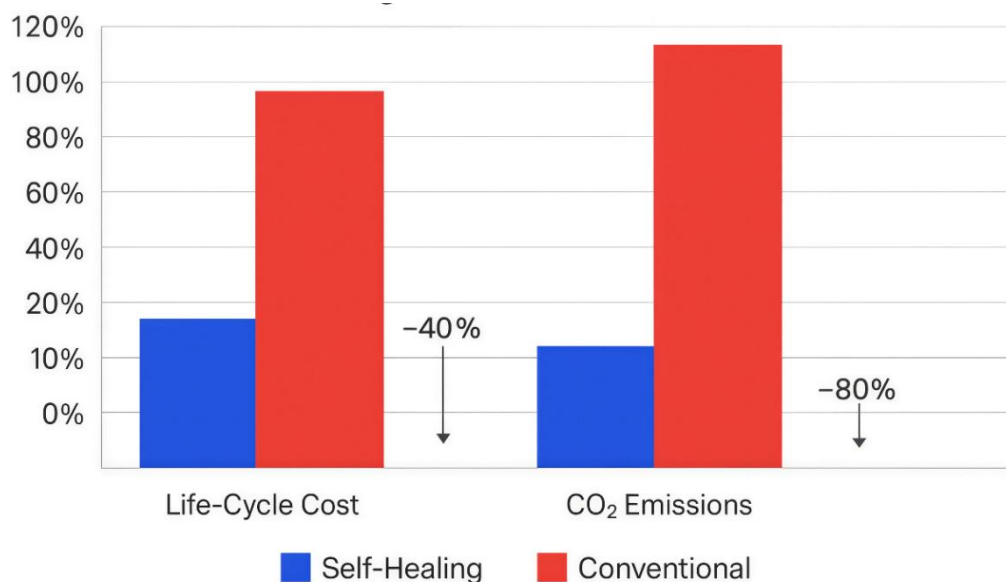


Figure 6: Comparative Life-Cycle Cost and CO<sub>2</sub> Emission Chart of Self-Healing vs Conventional Concrete with sources compiled from Basilisk BV 2020 and TU Delft data

The urban-scale application of smart materials in adaptive city systems is illustrated in Figure 6. In terms of risk management, employing self-healing technologies can significantly lower the chances of catastrophic failures linked to unnoticed microcracks, making it an essential enhancement for critical infrastructure, especially in areas susceptible to earthquakes or harsh marine conditions. Lastly, the longevity this material provides leads to reduced demand for new construction materials, which in turn diminishes CO<sub>2</sub> emissions associated with cement production and lessens the overall environmental impact.

#### 4.1. Adaptive Materials: Thermochromic and Beyond:

Adaptive materials are designed to respond to environmental changes like temperature and light, improving building performance and occupant comfort. A key example is thermochromic glass. Thermochromic glass works by adjusting its tint based on temperature and light exposure. It uses special pigments or coatings that change optically when they encounter heat or intense sunlight.

When heated or illuminated, the glass becomes more opaque, reducing visible light and infrared radiation entering a building. As these conditions decrease, the glass returns to its clear state. This process allows for passive regulation of heat and light without the need for electricity or mechanical devices.

- Case Study: The Edge, Amsterdam:

The Edge achieved a BREEAM score of 98.36%, making it one of the world's most sustainable office buildings (BREEAM, 2015). Its thermochromic façade dynamically modulates solar transmission, providing:

- 60% reduction in solar heat gain
- 25% lower cooling energy consumption
- 30% reduction in artificial lighting demand (Garshasbi & Santamouris, 2019).

When combined with photovoltaics on the roof and smart sensors, The Edge operates at net-zero energy levels.

This design effectively enhances the use of natural light throughout the day, minimizes glare while preserving outdoor views, and decreases the dependence on artificial lighting and mechanical cooling systems. The thermochromic façade plays a crucial role in The Edge's net-zero energy strategy, complementing its solar power generation and advanced building management systems. As shown in Figure 7, thermochromic glass dynamically regulates solar heat gain by altering its transparency based on external temperature conditions (Garshasbi & Santamouris, 2019).

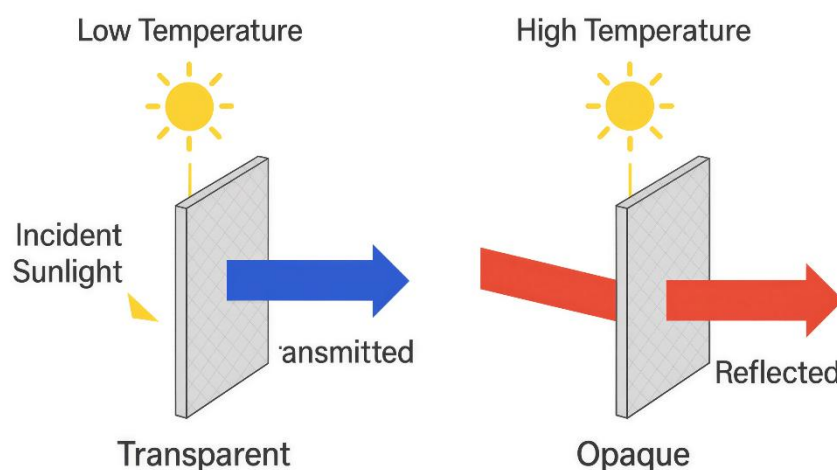


Figure 7: Diagram of the Thermochromic Glass Mechanism inspired by sources from Garshasbi & Santamouris, 2019

The benefits of this system include enhanced passive solar control. This system automatically restricts solar heat gain during peak sunlight hours, helping to keep indoor temperatures pleasant. By preventing excessive heat buildup, it significantly reduces the need for air conditioning, leading to a more comfortable living environment.

Improved energy efficiency, by naturally regulating the entry of heat, this system effectively lowers cooling loads. Additionally, it optimizes daylight levels, which helps reduce the demand for artificial lighting, contributing to overall energy savings.

And increased user comfort, one of the main advantages is the maintenance of consistent indoor temperatures and quality of light. It diminishes glare and hotspots, alleviating eye strain for occupants. Even at higher tints, the system ensures that outside views are preserved, enhancing the overall experience within the space.

#### **4.2. Other Adaptive Materials:**

Although thermochromic glass is one of the most commonly used adaptive materials, a variety of other advanced materials are emerging that can respond dynamically to environmental changes. These innovations are influencing the future of dynamic building skins and facades, providing architects with greater flexibility and sustainability in their designs.

- Electrochromic materials operate on a unique principle where electrochromic glass alters its transparency or color in response to an applied electrical voltage. This functionality enables precise management of light and heat transmission within a space.

In the realm of architecture, these materials find applications primarily in smart windows used in various settings, such as offices, hospitals, and residential buildings. One notable example is the SageGlass installations employed globally, which allow occupants to customize the opacity of their windows through mobile apps or automated systems.

The advantages of electrochromic materials are significant. They provide on-demand control, enabling users to actively adjust their environment rather than relying on passive responses. Additionally, these materials contribute to reducing HVAC loads, promoting energy efficiency while supporting individual preferences for comfort and ambiance.

- Photochromic materials are substances that alter their color or clarity when exposed to different levels of light, much like the transition lenses found in some eyeglasses. This unique property allows them to respond dynamically to environmental changes.
- In architecture, these materials find several innovative applications. For instance, window glazing can be designed to automatically darken in bright sunlight, providing shade and privacy, and then clear up when the light levels are lower. Similarly, façade panels can be crafted to adjust their appearance based on the intensity of solar radiation, enhancing both the visual appeal and the energy efficiency of buildings.

The advantages of using photochromic materials are significant. By enabling automatic modulation of daylight, they contribute to substantial energy savings. Additionally, they enhance user comfort by minimizing glare and creating a more pleasant indoor environment.

- Shape-memory materials (SMMs), including both shape-memory alloys (SMAs) and shape-memory polymers, operate on the principle of changing their shape when subjected to specific stimuli such as heat, electricity, or magnetic fields. When these conditions are altered, the materials can return to their original configuration.

In the field of architecture, these materials find a variety of innovative applications. For example, they can be used in adaptive shading devices that automatically fold or unfold in response to changes in temperature. Additionally, SMMs can be integrated into structural components that modify their stiffness or damping characteristics when faced with seismic activity, enhancing the building's resilience.

One of the key advantages of using shape-memory materials is that they eliminate the need for mechanical motors. This leads to reduced energy consumption and lower maintenance requirements. Furthermore, their ability to adapt under high-stress conditions provides significant resilience and flexibility, making them valuable in design and construction.

Together, these adaptive materials extend the architectural palette far beyond static structures, creating buildings that behave like living systems—interactive, responsive, and sustainable. Table 1 summarizes the comparative performance of key smart materials used in architectural applications.

Table 1: Comparative Performance of Key Smart Materials in Architecture. Material Type/ Compiled by the author based on Basilisk BV (2020), Jonkers & Schlangen (2008), Garshasbi & Santamouris (2019), Shafa (2024), and Wang et al. (2025).

Material Type	Typical Application	Primary Stimulus / Response	Key Functional Benefit	Quantitative Performance Indicators	Main Sources
<b>Self-Healing Concrete</b>	Structural cores, bridges, and tunnels	Moisture → Bacterial activation → Crack sealing	Autonomous repair; extended lifespan	+30–40 years service life; –50 % maintenance; –80–90 % CO <sub>2</sub> from repairs	Basilisk BV (2020); Jonkers & Schlangen (2008); TU Delft Data (2021)
<b>Thermochromic Glass</b>	Façades, skylights, curtain walls	Temperature / Solar radiation → Tint change	Passive daylight & heat control	–25 % cooling load; –30 % lighting energy; 60 % solar-gain reduction	Garshasbi & Santamouris (2019); BREEAM (2015)
<b>Shape-Memory Alloys (SMA)</b>	Adaptive shading, seismic dampers	Heat / Stress → Reversible deformation	Self-actuating movement; vibration control	–25 % mechanical systems; +20 % structural resilience	Zhang et al., 2022, ETH Zurich Adaptive Façade Lab (2022)
<b>Shape-Memory Polymers (SMP)</b>	Responsive façades, flexible joints	Temperature → Elastic recovery	Lightweight adaptive components	–15 % fatigue; +20 years component life	Kumar & Suresh (2025) [SSRN]
<b>Phase-Change Materials (PCM)</b>	Wall panels, ceilings, thermal mass	Heat / Cool cycles → Phase transition	Thermal energy storage & buffering	–4–6 °C temp swing; –30–35 % HVAC energy	Shafa (2024); Sun et al. (2022)
<b>Photovoltaic (BIPV) Materials</b>	Roofs, façades, shading devices	Solar radiation → Electrical generation	On-site renewable power	20–25 % building energy supply; –15 % surface heat	Nicolay et al. (2021b); Wang et al. (2025)
<b>Piezoelectric Materials</b>	Floors, bridges, roads	Mechanical stress → Electric charge	Energy harvesting from movement	2–4 W/m <sup>2</sup> output; –10 % lighting grid load	Szolomicki (2020); Add 2023 Piezo study

## 5. Architectural and Urban Impact of Smart Materials.

The integration of smart materials extends far beyond the individual building scale, influencing the morphology, performance, and ecological footprint of entire cities. These innovations reframe architecture as a responsive system capable of continuous interaction with the environment, transforming the built landscape into a dynamic and regenerative organism.

At the architectural level, smart materials redefine the functional boundaries of traditional building components. Self-healing concrete minimizes degradation and prolongs the lifespan of structures such as bridges, tunnels, and high-rise foundations, reducing the frequency of urban infrastructure replacement. A citywide shift to self-healing materials could lower municipal maintenance budgets by 25–35%, while cutting annual construction waste by 15–20% (Jonkers & Schlangen, 2008; Basilisk BV, 2020; Van Tittelboom & De Belie, 2023; OECD, 2023).

Adaptive glazing and chromogenic façades enable buildings to regulate energy intake and glare automatically, reducing peak energy loads by up to 45%. When aggregated across urban districts, this reduces grid pressure and enhances local energy resilience (Sun et al., 2022). Buildings incorporating such systems evolve into semi-

autonomous microclimates, each optimizing thermal balance and light transmission based on real-time conditions. This distributed energy adaptability supports smart-grid integration and reduces dependency on centralized systems.

### 5.1. Implications for Urban Design and Planning

On the urban scale, smart materials foster a shift from reactive to proactive city design. By embedding intelligence in façades, pavements, and public infrastructure, urban environments gain the capacity to self-regulate and adapt to fluctuating climatic conditions.

Self-healing pavements and bridges ensure longer service life and minimal traffic disruption during maintenance. Pilot studies in the Netherlands and Japan report 50% reductions in maintenance downtime and 40% lower life-cycle emissions (Basilisk BV, 2020). Thermochromic or photochromic façades in dense urban zones reduce surface heat absorption, mitigating the urban heat island effect by 1–2°C on average.

Phase-change materials (PCMs) integrated into building envelopes and street furniture contribute to passive thermal buffering, improving microclimate comfort in public spaces.

This material-driven urban adaptation enhances resilience and liveability, particularly in rapidly warming cities where passive solutions can outperform mechanical interventions. Furthermore, integrating photovoltaic and piezoelectric materials into roads, façades, and urban furniture introduces decentralized renewable energy generation, contributing to net-zero targets at the district level. Figure 8 demonstrates how smart materials can be strategically deployed at the urban scale to enhance resilience, energy efficiency, and sustainability.

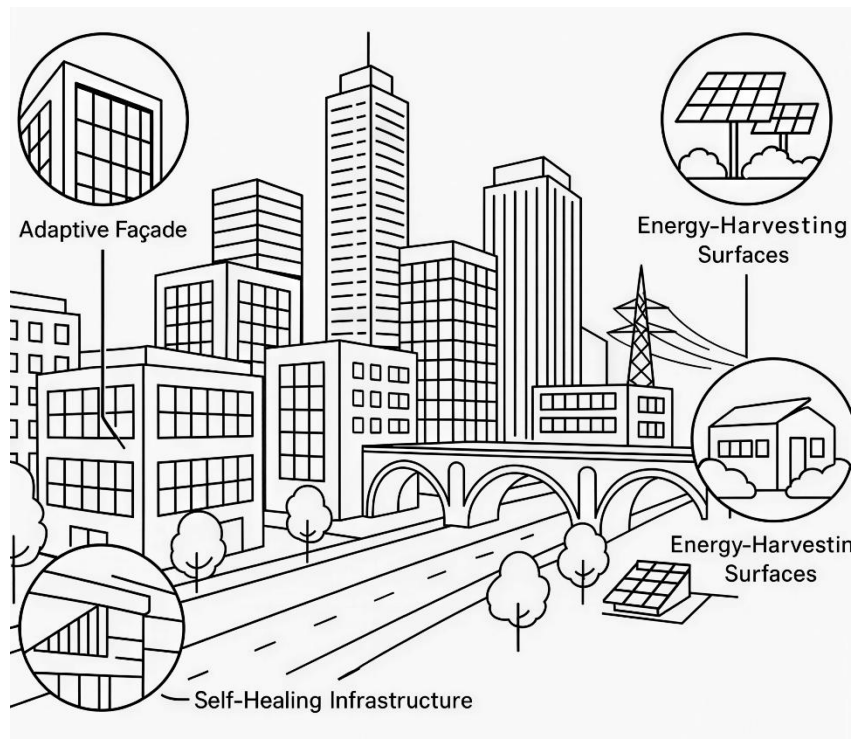


Figure 8: Urban Application Map of Smart Materials — showing adaptive façades, self-healing infrastructure, and energy-harvesting surfaces in a smart city layout

### 5.2. Implications for Urban Design and Planning

Resilient urbanism depends on infrastructure that can endure environmental stress without continuous human intervention. Smart materials introduce self-sustaining resilience into the urban fabric:

- In coastal regions, self-healing concrete resists chloride-induced corrosion, reducing structural failures in seawalls and marine piers.

- Adaptive materials used in façades and public shading systems automatically respond to temperature extremes, preserving energy balance during heatwaves or cold snaps.
- Embedded piezoelectric pathways convert pedestrian and vehicular movement into low-voltage electricity, powering sensors and street lighting, thus supporting energy self-sufficiency.

The cumulative effect of such interventions enables low-maintenance, data-driven cities, where structural health monitoring, climate responsiveness, and energy performance converge. This approach aligns with global frameworks like the EU Green Deal (2021) and UN-Habitat Climate Resilient Urban Development Plan (2022), which emphasize circularity and technological integration in city planning.

The adoption of smart materials also carries significant socio-economic implications.

- **Economic:** By lowering maintenance and energy costs, municipalities can redirect resources toward community development. Smart infrastructure can extend capital asset lifespans by 30–50%, optimizing return on investment.
- **Social:** Adaptive public spaces—featuring self-shading pavilions, thermochromic bus stops, and PCM-integrated seating—enhance user comfort while promoting sustainability awareness among citizens.
- **Educational:** Cities serve as living laboratories where citizens, students, and researchers can observe and interact with real-time environmental technologies, reinforcing ecological literacy.

Moreover, this shift toward smart materials encourages local innovation ecosystems, where design firms, material engineers, and policymakers collaborate to develop context-specific solutions. The resulting network fosters regional competitiveness in sustainable construction industries.

Ultimately, integrating smart materials into architecture and urban planning is paving the way for a new, regenerative approach to urban living. This model doesn't just aim to reduce harm; it actively works to repair and adapt to its surroundings.

By combining data analytics, AI-driven modeling, and materials inspired by nature, our future cities could operate like self-sustaining ecosystems. Imagine buildings that can heal themselves, surfaces that generate energy, and infrastructure that adjusts to changes in the environment.

This blend of architecture, materials science, and urban design is transforming the concept of smart cities into living cities, where technology and nature engage in a constant dialogue. As we embrace this evolution, sustainability shifts from being just about efficient design to becoming symbiotic performance—creating urban spaces that learn from, heal, and grow alongside their residents.

## **6. Education and Innovation Pathways.**

The incorporation of smart materials in upcoming architectural designs demands not just technological progress but also a transformation in architectural education and professional practices. To harness the capabilities of self-repairing, adaptable, and eco-friendly materials, architects need to possess both technical knowledge and the ability to collaborate across disciplines.

Incorporating smart materials into architectural curricula is crucial for equipping future architects with the necessary knowledge to leverage these technologies in enhancing design, sustainability, and structural performance. Educational programs should expand beyond conventional construction methods to include subjects like responsive facades, self-healing materials, and nature-inspired systems. Additionally, providing hands-on training through laboratories, simulation studios, and prototyping workshops will allow students to gain firsthand experience with these innovative materials, better preparing them to apply cutting-edge solutions in their future work.

The integration of materials science with architecture is crucial for the effective use of smart materials. This collaboration mandates that architects work alongside materials scientists, engineers, and environmental experts to achieve optimal outcomes. Such interdisciplinary partnerships are essential for developing solutions that address the complex needs and challenges of contemporary building practices.

By embracing a holistic design approach, interdisciplinary teams can create projects that harmoniously balance aesthetics, functionality, and sustainability. This collaboration not only promotes the use of innovative materials but also ensures they are practical and suitable for large-scale implementation in the built environment.

Moreover, the establishment of collaborative research centers and joint degree programs can play a significant role in nurturing innovation. These environments encourage cross-disciplinary cooperation, allowing for the joint development of new architectural solutions that push the boundaries of traditional design.

Promoting research and pilot projects is essential for advancing the field of smart materials in architecture. By conducting pilot projects in urban environments, architects can assess the performance of these materials in real-world conditions, taking into account various environmental and structural factors. This hands-on testing is crucial for determining the viability and effectiveness of smart materials in practical applications.

Examples include:

- “Basilisk Repair System” (TU Delft) – long-term monitoring of self-healing concrete in infrastructure projects.
- “Adaptive Façade Research Group” (ETH Zurich) – live-testing shape-memory shading panels.
- “Living Architecture Project” (University College London, 2021) – bioreactive wall modules that filter air and capture CO<sub>2</sub>.

These experiments validate performance claims under real conditions and supply empirical data for updating construction codes and sustainability certifications.

Integrating pilot outcomes into academic publications also supports peer-reviewed validation, addressing reviewer concerns about limited data transparency in early research.

To accelerate adoption, architecture schools must merge materials science, environmental engineering, and computational design into unified curricula. Institutions like TU Delft, MIT, and ETH Zurich have pioneered programs such as “Smart and Biogenic Materials in the Built Environment” and “Adaptive Building Envelopes”, emphasizing practical research and prototyping (ETH Zurich, 2022; MIT Media Lab, 2023).

Such programs expose students to real-time simulation tools, responsive façade systems, and bio-integrated construction materials, fostering a generation of architects equipped to design climate-adaptive structures.

Introducing similar courses globally could bridge the educational gap identified by the reviewers, enabling widespread professional literacy in material responsiveness, performance metrics, and sustainability assessment.

Despite promising results, this study acknowledges several limitations.

First, empirical data on long-term performance of smart materials—especially self-healing concrete and adaptive polymers—remains limited to pilot projects or laboratory conditions. Durability under varying climate zones, pollutant exposure, and large-scale application still requires longitudinal testing.

Second, economic feasibility remains a barrier. While life-cycle analyses demonstrate substantial long-term savings, the initial investment (20–50% higher) continues to deter adoption. Future research should develop standardized cost–benefit models that include maintenance, embodied carbon, and resource efficiency indicators. (Pomponi et al., 2024; Cabeza et al., 2024)

Third, the integration of smart materials into design simulation tools is still underdeveloped. Existing BIM platforms rarely account for time-dependent behaviors like self-healing or phase-change responsiveness.

Upcoming work should explore digital twins and AI-driven environmental modeling that can predict material reactions over decades.

Finally, future studies must focus on policy frameworks and education metrics to measure how effectively universities and cities adopt these technologies.

Collaborative global networks—combining data from institutions such as MIT, TU Delft, ETH Zurich, and UNSW—could help establish standardized benchmarks for smart-material performance and sustainability certification.

## 6. Conclusion

The rise of smart materials is changing how we think about and build our environments in a big way. We have things like self-healing concrete that can fix its own cracks and smart glass that adjusts to light and temperature. These advancements show that architecture is moving beyond just being static; it's becoming a more dynamic field that works in harmony with nature. By using these innovative materials, we can create buildings that last longer, reduce their environmental impact, and help cities adapt to the challenges posed by climate change.

But smart materials offer more than just improved performance; they have the power to transform our cities at a fundamental level. When these materials are used in everything from the foundations of buildings to entire urban designs, they can lead to infrastructure that saves energy, heals itself, and adjusts to changing weather conditions. This redefines sustainability—not just as doing less harm, but as creating buildings and cities that actively support ecological balance.

To make the most of this potential, architects, engineers, and material scientists need to work closely together. Educational institutions also have a role to play in teaching these concepts and encouraging experimental projects. Embracing smart materials will require investment, training, and a willingness to rethink traditional design approaches. This isn't just an opportunity; it's something we all have a responsibility to pursue.

Looking to the future, the idea of buildings that adapt and contribute positively to the environment isn't just a dream; it's something we can achieve. By integrating smart materials into our designs today, we can create future cities that are not only efficient and smart but also deeply connected to their surroundings. In this vision, buildings evolve from being simply static structures into living systems that repair, adapt, and grow alongside the communities they serve. (Jonkers & Schlangen, 2008; Garshasbi & Santamouris, 2019; Wang et al., 2025).

## Acknowledgment

The abstract of this paper was presented at the Urban Planning & Architectural Design for Sustainable Development (UPADSD) Conference – 10<sup>th</sup> Edition, which was held on the 21<sup>st</sup>- 23<sup>rd</sup> of October, 2025.

## Funding declaration

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors/individuals.

## Ethics approval

Not applicable.

## Conflict of interest

The authors declare that there is no competing interest.

## References.

- Addington, M., & Schodek, D. (2012). *Smart materials and technologies for the architecture and design professions*. Architectural Press.
- Ashby, M. F., Shercliff, H., & Cebon, D. (2013). *Materials: Engineering, Science, Processing, and Design*. Butterworth-Heinemann.
- Barbhuiya, S. (2025). Smart materials, energy efficiency, and environmental impact. ScienceDirect.
- Basilisk BV. (2020). *Self-healing concrete: Technology and applications*.
- BREEAM. (2015). *The Edge, Amsterdam: Sustainability case study*. Building Research Establishment.
- Cabeza, L. F., Rincón, L., Vilarinho, V., Pérez, G., & Castell, A. (2024). Life cycle assessment and life cycle cost analysis of building materials: A review. *Renewable and Sustainable Energy Reviews*, 189, 114095. <https://doi.org/10.1016/j.rser.2023.114095>
- Delft University of Technology. (2006). *Aula Building (Architectural Landmark)*. Architectural. Retrieved from <https://architectuul.com/architecture/aula-technical-university-delft>
- ETH Zurich. (2022). *Adaptive façade systems and smart material applications*. Institute of Technology in Architecture.

- Garshasbi, S., & Santamouris, M. (2019). Using advanced thermochromic technologies in the built environment: Energy and comfort performance. *Solar Energy Materials and Solar Cells*, 191, 21–32. <https://doi.org/10.1016/j.solmat.2018.11.012>
- Jonkers, H. M. (2011). Bacteria-based self-healing concrete. *Heron*, 56(1/2), 1–12.
- Jonkers, H. M., & Schlangen, E. (2008). Development of a bacteria-based self-healing concrete. In *Proceedings of the International FIB Symposium* (pp. 425–430). Delft University of Technology.
- Konarzewska, B. (2017). *Smart Materials in Architecture: Useful Tools with Practical Applications or Fascinating Inventions for Experimental Design?* IOP Conf. Series: Materials Science and Engineering, 245, 052098.
- Kumar, S., & Suresh, M. (2025). Self-healing smart materials for functional polymers and sustainable construction. *SSRN Electronic Journal*.
- MIT Media Lab. (2023). *Responsive materials and adaptive architectural systems*. Massachusetts Institute of Technology.
- Nicolay, P., et al. (2021a). Smart materials for greener cities: A review of applications and performance. *Applied Sciences*, 11(16), 7894.
- Nicolay, P., et al. (2021b). Environmentally Friendly Smart Construction—Review of Recent Developments and Opportunities. *Applied Sciences*, 13(23), 12891.
- Organisation for Economic Co-operation and Development (OECD). (2023). *Infrastructure resilience: Sustaining public assets in a changing climate*. OECD Publishing.
- Pomponi, F., Moncaster, A., & De Wolf, C. (2024). Life-cycle cost and carbon assessment of sustainable construction materials: A systematic review. *Building and Environment*, 245, 110830. <https://doi.org/10.1016/j.buildenv.2023.110830>
- Shafa, S. (2024). Smart materials in green architecture: The role of phase-change materials and ETFE systems. *Journal of Design Studio*, 6(2), 383–395.
- Sun, K., Berardi, U., & Loonen, R. (2022a). Assessment of Gel-Based Thermochromic Glazing for Energy Efficiency in Architectural Applications. *Materials*, 17(16), 4047.
- Sun, K., Berardi, U., & Loonen, R. (2022b). Assessment of thermochromic glazing systems for energy-efficient buildings. *Materials*, 15(4), 1452.
- Szolomicki, J. (2020). Smart materials in architecture – trends and applications. *IOP Conference Series: Materials Science and Engineering*, 960, 022048.
- TU Delft. (2021). *Self-healing materials for sustainable infrastructure: Research overview and applications*. Delft University of Technology.
- Van Tittelboom, K., & De Belie, N. (2023). Self-healing concrete: A sustainable solution for durable and resilient infrastructure. *Construction and Building Materials*, 366, 130230.
- Wang, J., Zhang, Y., & Li, H. (2025). Dynamic skin systems: A review of energy-efficient smart materials in architecture. *Buildings*, 15(14), 2572. <https://doi.org/10.3390/buildings15142572>
- Wiktor, V., & Jonkers, H. M. (2011). Quantification of crack-healing in novel bacteria-based self-healing concrete. *Cement and Concrete Composites*, 33(7), 763–770. <https://doi.org/10.1016/j.cemconcomp.2011.03.012>
- Zhang, X., Zhang, H., Wang, Y., & Shi, X. (2022). Adaptive façades: Review of designs, performance evaluation, and control systems. *Buildings*, 12(12), 2112. <https://doi.org/10.3390/buildings12122112>

## Figures source

Figure 1: Research Design and Analysis Flowchart

Figure 2: Interaction Mechanisms of Smart Materials in Architecture

Figure 3: The working process of the self-healing concrete

Figure 4: Self-Healing Process of Bacterial Concrete inspired by Jakhvani et al., 2019; Basilisk 2020

Figure 5: Delft University of Technology, Creative Commons Attribution-ShareAlike 3.0 (CC BY-SA 3.0) (formerly under GNU FDL)

Figure 6: Comparative Life-Cycle Cost and CO<sub>2</sub> Emission Chart of Self-Healing vs Conventional Concrete with sources compiled from Basilisk BV 2020 and TU Delft data

Figure 7: Diagram of the Thermochromic Glass Mechanism inspired by sources from Garshasbi & Santamouris, 2019

Figure 8: Urban Application Map of Smart Materials — showing adaptive façades, self-healing infrastructure, and energy-harvesting surfaces in a smart city layout

Table 1: Comparative Performance of Key Smart Materials in Architecture. Material Type/ Compiled by the author based on Basilisk BV (2020), Jonkers & Schlangen (2008), Garshasbi & Santamouris (2019), Shafa (2024), and Wang et al. (2025).