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## Innovative Materials and Failure Prevention in Infrastructure: Towards Sustainable Construction with Social Impact

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### Abstract

*This article analyzes the role of innovative materials in the prevention of structural failures and their relationship with sustainability and social impact in construction. Through a multidisciplinary approach, the use of materials such as self-healing concrete, carbon fiber-reinforced polymers, nanomaterials, and recycled materials is examined. The methodology combines recent literature review and relevant case studies. It is shown that the implementation of these materials not only improves the structural strength and durability of infrastructure, but also reduces maintenance costs and generates social benefits by increasing urban resilience and promoting equity in access to safe infrastructure. Finally, a theoretical framework is proposed that articulates technical sustainability with social development, as a guide for decision-making in public policies and engineering projects.*

**Keywords:** Innovative Materials, Sustainability, Structural Failures, Social Impact, Infrastructure.

### Introduction

Infrastructure is an essential component for economic development, territorial connectivity and social welfare. However, their progressive deterioration, exposure to extreme weather events, and the use of traditional materials with a limited useful life have generated growing concerns about the durability, efficiency, and safety of civil constructions (García-Pérez, Torres, & Ramírez, 2022). In this context, the need to adopt innovative approaches that integrate emerging technologies and advanced materials has become imperative to respond to the challenges of the twenty-first century.

In parallel, the climate crisis has intensified pressure on the construction sector, responsible for approximately 39% of global carbon dioxide emissions (UNEP, 2020). Added to this is the growing vulnerability of urban and rural communities to phenomena such as floods, earthquakes or landslides, which expose not only structural failures, but also inequalities in access to safe infrastructure. Hence the urgency of moving towards a sustainable construction model that not only contemplates technical efficiency and the minimization of environmental impacts, but also incorporates a focus on social justice and community resilience (World Bank, 2023).

Recent studies have highlighted the potential of materials such as self-healing concrete, fiber-reinforced polymer composites, functional nanomaterials, and the use of recycled waste as

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structural aggregates (Xu, Liu, & Huang, 2022; Li & Zhang, 2023; Fernández & Gómez, 2021). These materials not only extend the life of structures, but significantly reduce maintenance costs, while decreasing the demand for non-renewable resources. In addition, its implementation in public projects has demonstrated tangible benefits in terms of generating local employment, improving the urban environment, and reducing disaster risk (Pérez & Andrade, 2022).

The present paper aims to analyze how the integration of these innovative materials contributes to the prevention of structural failures and the consolidation of a construction model with a positive social impact. It is based on the hypothesis that sustainability cannot be understood only as an environmental goal, but as an integrating principle of technical, economic and social dimensions. To this end, an updated literature review is used, complemented by relevant case studies in Latin America and Asia, where these solutions have been successfully applied in challenging contexts.

The article is structured in five sections: after this introduction, a theoretical framework is presented that contextualizes the main concepts related to innovative materials, sustainability and infrastructural justice; then the methodology used is detailed; Next, the results obtained from the analysis are presented; and finally, the conclusions and recommendations aimed at decision-makers, urban planners and civil engineers are presented.

## Theoretical Framework

### Innovation in Construction Materials

Advances in materials science have generated new solutions to extend the useful life of structures and improve their performance in the face of mechanical stresses, climate variability, and corrosion processes (Xu et al., 2022). These materials include self-healing concrete, nanomaterials, fiber-reinforced polymers, and recycled materials, all of which are considered pillars of innovation applied to infrastructure.

**Self-healing concrete**, for example, contains encapsulated agents—such as bacteria or microfibers—that activate healing processes of the material when moisture or cracks are detected, reducing maintenance costs and improving durability (Xu et al., 2022). Nanomaterials, such as metal oxides or carbon nanotubes, make it possible to modify the thermal, mechanical, and chemical properties of traditional compounds (Li & Zhang, 2023).

The main innovative materials applied in construction are summarized below in **Table 1**:

<i>Material</i>	<i>Featured Property</i>	<i>Main Application</i>	<i>Fountain</i>
<i>Self-healing concrete</i>	Self-healing of fissures	Pavements, tunnels, dams	Xu et al. (2022)
<i>Fiber-reinforced polymers</i>	High mechanical strength and lightness	Reinforcement of beams, bridges and walls	Rafiq et al. (2020)
<i>Nanomaterials</i>	Improved thermal and anti-corrosion properties	Protective coatings, cementitious mixtures	Li & Zhang (2023)
<i>Recycled materials</i>	Reducing emissions and reusing waste	Recycled concrete, eco-friendly bricks	Fernández & Gómez (2021)

Table 1. Main Innovative Materials and Their Applications In Infrastructure

## Prevention of Structural Failures

Structural failures are commonly attributable to material fatigue, load deformations, environmental deterioration, design errors, or lack of maintenance (García-Pérez et al., 2022). In response, modern structural engineering seeks strategies that anticipate and mitigate these risks through simulation-assisted design, predictive inspection, and especially through the use of materials with advanced properties.

The concept of **resilient design** promotes the construction of infrastructures that withstand and adapt to extreme events without losing critical functionality. In this context, innovative materials act as the first line of defense against cracking, plastic deformation, corrosion, and progressive collapse (Sosa et al., 2021).

## Sustainability in Construction

Sustainability in construction goes beyond energy savings. It involves designing infrastructures with **efficient life cycles**, a low ecological footprint, the possibility of reusing components and reducing the consumption of natural resources (UNEP, 2020). In this sense, **recycled materials with a low environmental impact** play an essential role.

According to Fernández and Gómez (2021), the use of slag, plastic waste and recycled aggregates reduces CO<sub>2</sub> emissions in the concrete production cycle by between 20% and 30%. Likewise, nanomaterials have been recognized for increasing the durability and reducing the porosity of structures exposed to aggressive agents, such as chlorides or sulfates (Li & Zhang, 2023).

**Table 2** presents key indicators associated with the sustainability of materials in infrastructure projects:

<i>Indicator</i>	<i>Description</i>	<i>Related Material</i>	<i>Environmental benefit</i>	<i>Fountain</i>
<i>CO<sub>2</sub> reduction</i>	Reduction of emissions in material production	Recycled concrete	Lower carbon footprint	Fernández & Gómez (2021)
<i>Structural self-healing</i>	Ability of the material to repair cracks without intervention	Self-healing concrete	Reduced maintenance and waste	Xu et al. (2022)
<i>Corrosion resistance</i>	Protection against moisture and aggressive agents	Coatings with nanomaterials	Increased durability and structural safety	Li & Zhang (2023)
<i>Reuse of solid waste</i>	Integration of waste materials into the structural mix	Recycled materials	Efficient construction waste management	Pérez & Andrade (2022)

Table 2. Sustainability Indicators in Construction Materials

## **Infrastructure with Social Impact**

Access to quality infrastructure is a determinant of human development. Engineering with a social focus promotes constructions adapted to local contexts, resilient and with community participation (Pérez & Andrade, 2022). This approach allows technological innovations to reach traditionally marginalized sectors, reducing risk, mobility, and service gaps.

The inclusion of local labor for the production of sustainable prefabricated components or the design of schools and health centers with improved indigenous materials are examples of how engineering can become a tool for social justice (World Bank, 2023).

### **Methodology**

This study adopted a **mixed** exploratory-descriptive approach, combining qualitative and quantitative techniques to comprehensively address the relationship between innovative materials, the prevention of structural failures and the social impact of sustainable infrastructures.

The research was divided into **three main methodological phases** : (1) systematic review of recent scientific literature, (2) analysis of case studies applied to relevant civil works in real contexts, and (3) formulation of an integrative analytical framework based on technical, environmental and social indicators.

#### **Phase 1: Systematic Review of Scientific Literature**

A systematic review of academic sources indexed in databases such as **Scopus, Web of Science, ScienceDirect and SpringerLink** was conducted. The following inclusion criteria were established:

- Publications between **2019 and 2024**.
- Articles related to **innovative materials, structural failures, sustainable construction, and equity in infrastructure**.
- Empirical studies, systematic reviews and meta-analyses.

Se utilizaron combinaciones de palabras clave en inglés y español como: “innovative construction materials”, “structural failure prevention”, “sustainable infrastructure”, “self-healing concrete”, “social impact construction”.

The initial search yielded **138 documents**, of which **56** were selected after applying the criteria of quality and relevance, following the **PRISMA protocol** (Page et al., 2021).

#### **Phase 2: Analysis of Case Studies**

Four representative case studies **were selected** for their level of innovation, social context and documented results. The projects were:

- *Reinforcement of rural bridges with CFRP in Peru.*
- *Implementation of self-healing concrete in urban sanitation networks in the Netherlands.*
- *Use of recycled materials in social housing in Colombia.*
- *Application of nanomaterials in coatings of marine structures in Japan.*

The analysis of the cases considered the following dimensions:

- **Technical indicators:** structural strength, durability, maintenance frequency.
- **Environmental indicators:** emission reduction, recycling, water footprint.
- **Social indicators:** accessibility, community participation, improvement of services.

Each case was examined using an analytical file that allowed the information to be systematized and structured comparisons to be established (Yin, 2018).

### Phase 3: Formulation of the Integrative Analytical Framework

Based on the literature and the cases analyzed, an **analytical model was built to evaluate the impact** of innovative materials on the sustainability and equity of infrastructure. This model articulates three interdependent axes:

- **Technical performance.**
- **Environmental sustainability.**
- **Social and community impact.**

A multi-criteria matrix **was applied** to weight the materials according to their overall performance, under the aforementioned criteria, assigning weights according to frequency and relevance in the studies reviewed (Fernández & Gómez, 2021; Li & Zhang, 2023).

PHASE	APPLIED TECHNIQUE	INSTRUMENT/PROCEDURE	EXPECTED RESULT	FOUNTA IN
LITERATURE REVIEW	Systematic Review (PRISMA)	Search in Scopus/Web of Science. Inclusion criteria 2019–2024	Identification of trends and gaps in the literature	Page et al. (2021)
CASE STUDIES	Comparative analysis	Technical, environmental and social assessment sheets	Understanding real-world applications and their impacts	Yin (2018)
ANALYTICAL FRAMEWORK	Multi-criteria evaluation matrix	Material weighting for comprehensive performance	Decision model for selecting sustainable materials	Fernández & Gómez (2021); Li & Zhang (2023)

Table 3. Methodological Techniques and Procedures By Phase

### Ethical Considerations and Limitations

Ethical criteria such as the **veracity of secondary sources**, respect for copyright, and confidentiality of **sensitive data** in case studies were guaranteed. The main constraint was the **uneven availability of detailed technical information** on certain projects in developing

## Results

The analysis carried out made it possible to establish empirical evidence on the positive impact of innovative materials in three fundamental dimensions: **prevention of structural failures**, **reduction of environmental impacts** and **generation of social benefits**. Based on the case studies and the bibliographic review, the results are synthesized at three levels: technical, environmental and social.

### Technical Performance: Failure Reduction and Increased Service Life

The innovative materials showed significant improvements in **structural strength, durability and maintenance frequency** compared to conventional materials.

MATERIAL	FAILURE REDUCTION (%)	ESTIMATE D LIFETIME INCREASE (%)	FREQUENCY OF MAINTENANCE	FOUNTAIN
SELF-HEALING CONCRETE	40–55%	30–50%	Annual inspection (no repair)	Xu et al. (2022)
FIBER-REINFORCED POLYMERS	50–70%	40–60%	Maintenance every 10 years	Rafiq et al. (2020)
NANOMATERIALS	60% (corrosion resistance)	25–35%	Review every 5 years	Li & Zhang (2023)
RECYCLED MATERIALS	30–40%	15–25%	Semi-annual maintenance	Fernández & Gómez (2021)

Table 4. Comparison of the Technical Performance of Innovative Materials

As can be seen, the **use of CFRP and self-healing concrete** reduced by more than half the interventions due to cracks or fatigue in critical structures such as bridges and sanitary collectors. Nanomaterials applied to marine surfaces showed particular efficacy against salt corrosion, which is crucial in coastal environments (Li & Zhang, 2023).

### Environmental Performance: Mitigation of Emissions and Resource Consumption

The materials analysed also demonstrated **substantial environmental benefits**, especially in terms of reducing CO<sub>2</sub> emissions and utilising industrial waste.

Material	CO <sub>2</sub> reduction per tonne (%)	Waste reuse (%)	Energy impact (kWh/m <sup>3</sup> )	Fountain
Self-healing concrete	10–15%	5–10%	850	Xu et al. (2022)
Fiber-reinforced	20–25%	0%	1100	Rafiq et al.

<b>polymers</b>				(2020)
<b>Nanomaterials</b>	5–8%	0%	950	Li & Zhang (2023)
<b>Recycled materials</b>	25–30%	35–50%	600	Fernández & Gómez (2021)

Table 5. Environmental Benefits of Innovative Materials in Construction

Concrete **with recycled aggregates**, used in social housing projects in Colombia, showed an average reduction of **28% in carbon emissions** compared to traditional mixtures, in addition to an energy saving of 25% in its production (Fernández & Gómez, 2021).

### Social Impact: Access, Employment and Community Resilience

Beyond physical and environmental performance, the social effects of applying these materials in community and public infrastructure projects were evaluated.

<i>Social indicator</i>	<i>Observed Result</i>	<i>Material involved</i>	<i>Fountain</i>
<i>Reduction of population at risk</i>	–35% in seismic and flood zones	Self-healing concrete, CFRP	World Bank (2023)
<i>Local job creation</i>	+22% during construction (technical training)	Recycled materials	Pérez & Andrade (2022)
<i>Improved access to services</i>	+18% in water and sanitation coverage through safe infrastructure	Nanomaterials, reinforced concrete	García-Pérez et al. (2022)
<i>Community Engagement</i>	+40% inclusion in project decisions	All materials (in collaborative models)	Rafiq et al. (2020)

Table 6. Social Results Linked to the Use of Innovative Materials

These results confirm that the use of innovative materials, especially when integrated into participatory processes, **contributes to infrastructural justice** and strengthens the resilience of vulnerable communities to natural hazards and territorial exclusion (Pérez & Andrade, 2022; World Bank, 2023).

### Multi-Criteria Integrative Analysis

Using the **constructed weighting matrix**, the relative contribution of each material was evaluated based on its technical, environmental and social performance. Weights from 1 to 5 were assigned to each dimension and a composite sustainability index (SCI) was generated.

<i>Material</i>	<i>Technical Performance (1–5)</i>	<i>Environmental (1–5)</i>	<i>Social (1–5)</i>	<i>Total ICS (average)</i>
<i>Self-healing concrete</i>	4.5	3.5	4.0	<b>4.0</b>
<i>Fiber-reinforced polymers</i>	5.0	3.0	3.5	<b>3.8</b>
<i>Nanomaterials</i>	4.0	3.2	4.0	<b>3.7</b>
<i>Recycled materials</i>	3.5	5.0	4.5	<b>4.3</b>

The best overall performance was observed in recycled **materials**, thanks to their low environmental impact and social benefits when manufactured locally. However, in strictly structural terms, **CFRP and self-healing concrete** continue to be the most efficient.

## Conclusions

The findings of this research confirm that **innovative materials** represent a key tool in the transformation of the construction sector towards a truly **sustainable, resilient and inclusive model**. Its incorporation into the design and execution of infrastructures not only **significantly improves the technical performance** of the works, but also **contributes to the reduction of environmental impacts** and **generates tangible social benefits**, especially in vulnerable or historically excluded communities.

In technical terms, materials such as **self-healing concrete** and **fiber-reinforced polymers (CFRP)** have proven to be effective in **preventing structural failures**, extending the life of constructions and reducing corrective maintenance costs. These materials allow for an increase of up to 50% in resistance to cracks and deformations, which is a fundamental advance in terms of safety and structural efficiency (Xu et al., 2022; Rafiq et al., 2020).

From an environmental perspective, the use of **recycled materials** has managed to reduce carbon dioxide emissions per ton of concrete produced by between 25% and 30%, while promoting the circular economy in the construction sector (Fernández & Gómez, 2021). Nanomaterials, on the other hand, have proven valuable in improving corrosion and fire resistance in structures subjected to extreme weather conditions, which is essential in the face of the challenges of climate change (Li & Zhang, 2023).

Regarding the **social impact**, the results indicate that the application of these materials can contribute to **reducing exposure to the risk of natural disasters**, improving access to basic services, generating technical-local employment, and promoting **community participation** in infrastructure projects (Pérez & Andrade, 2022; World Bank, 2023). These positive externalities are crucial to move towards an approach to **infrastructure as a right** and not as a privilege.

Importantly, the effective use of innovative materials requires not only technological updating, but also **appropriate regulatory, institutional, and educational frameworks**. Knowledge transfer, the training of qualified labor, and the articulation between universities, the public sector, and construction companies are essential conditions for scaling these solutions at the regional and global levels (UNEP, 2020).

Finally, this study proposes that any sustainable infrastructure strategy with social impact must simultaneously consider **technical, environmental and human criteria**. The choice of materials must be informed by multi-criteria evaluations, such as the one proposed in this article, which allow decisions to be made based on evidence, context and territorial development objectives.

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