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THE ROLE OF NANOTECHNOLOGY IN THE MODERN CONSTRUCTION INDUSTRY: APPLICATIONS AND FUTURE PROSPECTS

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Abstract

This paper examines various applications of nanotechnology in the construction industry and the technical advantages they provide. The incorporation of nanoparticles into concrete, steel, and polymer-based materials has significantly enhanced structural durability, energy efficiency, and resistance to corrosion. Additionally, self-healing concrete systems and nano-enhanced fire-resistant coatings stand out as innovative approaches in this field. The aim of this paper is to analyze the current state of these technologies, highlight their practical applications, and shed light on their future prospects.

Keywords: *nanotechnology; self-healing concrete; nano-coatings*

1. Introduction

The use of nanoparticles in construction materials has, in recent years, laid the foundation for innovative approaches in the field. Due to their unique surface effects, high reactivity, and mechanical strength, nanoscale particles enhance the physicochemical properties of traditional materials such as concrete, steel, asphalt-concrete, and brick. Some nanomaterials – particularly silver – are already used in thousands of consumer products. In 2015, the global nanomaterials market exceeded \$14 billion, and it was projected to reach \$55 billion by 2022. In construction, nanoparticles not only improve structural strength and durability, but also contribute to ecological and economic efficiency by optimizing energy consumption and material use, aligning with the "doing more with less" principle. However, scientific and legal uncertainties regarding their long-

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term effects on human health and the environment remain unresolved. Therefore, both the technical potential and bioethical concerns must be carefully balanced when evaluating the application of nanotechnology in the construction sector [1].

2.1. Application of different nanomaterials in construction materials

In recent years, remarkable innovations have been observed in the functional capabilities of construction materials. A study conducted by Chen and colleagues demonstrates that materials enriched with nanoparticles are not only mechanically more durable but also gain additional functionalities [2]. In this context, titanium dioxide (TiO_2) nanoparticles, known for their photocatalytic properties, stand out. According to research, concrete surfaces enriched with TiO_2 acquire self-cleaning properties under ultraviolet (UV) radiation [3].

Another study, conducted by Apolinario and his collaborators, examined concrete mixtures containing silicate nanocapsules. Initially, these samples were kept in a humidity chamber for 180 days and subsequently tested under natural atmospheric conditions. The results revealed that nanocapsules demonstrated high adaptability to humid environments and enabled the full recovery process of the concrete [4].

At the same time, graphene-based insulation materials attract attention due to their energy efficiency. A study published in the International Journal of Nanotechnology confirms that these materials reduce thermal conductivity by 40% compared to traditional insulation solutions, significantly decreasing energy consumption in buildings [5].



Fig. 1. The working principle of self-cleaning glass [6].

Zinc oxide (ZnO) nanoparticles have shown significant effects in the construction sector, particularly when incorporated into concrete mixtures. The application of ZnO accelerates the setting process of concrete, increases its water resistance, and reduces the likelihood of microcrack formation [7].

According to the literature, nano-sized tungsten oxide (WO_3) particles exhibit superior protective properties in epoxy resin systems compared to their microscale counterparts. Moreover, the inclusion of nano- ZnO (nZnO) particles in the same system further enhances the protective effect. For this reason, WO_3 nanoparticles were preferred in the referenced study for protection purposes [8].

Silica-based nanoparticles reduce the porosity of concrete, significantly limiting the penetration of water and other aggressive agents into the material. As a result, they help prevent the degradation process of concrete [1].

Silver nanoparticles are known for their antibacterial properties. Research indicates that these particles reduce bacterial growth by up to 90% in medical environments. They can inhibit microbial activity on surfaces, thereby extending the service life of materials [9].

Carbon nanotubes (CNTs), due to their large surface area and exceptional mechanical properties, are used as nanofillers in concrete structures. Studies conducted by Konsta-Gdoutos and colleagues have demonstrated, using scanning electron microscopy (SEM), that CNTs more effectively fill the voids in concrete [1, 10]. The addition of CNTs improves concrete's impermeability to water and salts, thereby significantly enhancing its durability [1, 10].

Overall, nanoparticles are widely applied in modern construction not only in concrete but also in steel, glass, coatings, fire-resistant materials, and structural monitoring systems.

2.2. Biological mechanisms and nanotechnological solutions in self-healing concrete technology

Self-healing concrete technology, developed to enhance the durability of modern construction materials, marks a revolutionary step in the industrial application of nanobiotechnology. This innovative approach relies on the use of specifically selected microorganisms and nanomaterials. Cracking is an inevitable property of concrete. In this study, three *Bacillus* species—*B. pseudofirmus*, *B. cohnii*, and *B. halodurans*—were used. Cracks with a diameter of 0.13 mm were repaired with bacterial calcium carbonate within 14–28 days, depending on the bacterial strain. *B. pseudofirmus* showed the best performance. Alkaliphilic bacteria such as *Bacillus pseudofirmus* are embedded in the concrete mixture using nanocapsules. This initiates a biological process that catalyzes the reaction of calcium lactate into calcium carbonate when cracks form in the concrete. The resulting calcite crystals are densely deposited into the cracks, restoring up to 80–90% of the original material strength [11].

Research has demonstrated that the application of this method increases the service life of concrete by at least 20–25% and significantly reduces repair costs. Scientists also estimate that using nanocapsules can extend the lifespan of the embedded bacteria by more than 50 years.

Additionally, the fungus *Trichoderma reesei* has shown a remarkable ability to produce calcite without losing efficiency, even under high pH conditions, making it a promising alternative biological agent [12].

One notable example of the successful implementation of this technology was a project in Rijen, the Netherlands, where self-healing concrete was used in a railway underpass. A mixture of bacteria and nutrients was applied, resulting in the autonomous healing of cracks and an extended structural lifespan [13].

2.3. Nanoparticles in steel. fire-resistant materials with nano-enhancements

Research indicates that the structural integrity of steel significantly decreases with rising temperatures. It is reported that above 750°F (approximately 399°C), the load-bearing capacity of steel constructions begins to decline. At 1000°F (537°C), the material loses approximately 50% of its original strength [14].

To address these issues, nanotechnological approaches have been employed, particularly by incorporating nanoscale particles into the structure of steel. Such nano-enhancements enable the preservation of structural integrity even under extreme temperatures (e.g., 1000°F). As a result,

this technology allows for the development of steel types that are not only more durable but also more resistant to corrosion [14].

A noteworthy example in this field is the MMFX2 grade of steel. This material possesses nanostructured and corrosion-resistant properties and offers a level of protection comparable to that of stainless steel. Furthermore, it is more cost-effective in terms of production and has been officially approved in the United States for general construction purposes [15].

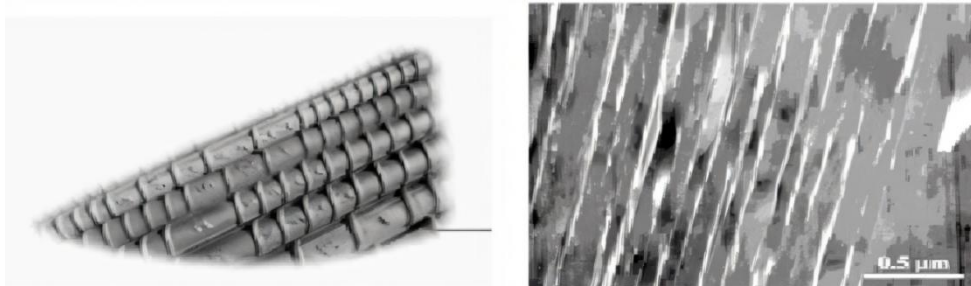


Fig. 2. Nanostructurally modified steel reinforcement [15].

Fire-resistant materials with nano-additives. The use of halogen-based flame retardants has been banned in several countries due to their harmful effects on the environment and human health. Traditional flame retardants include substances such as bitumen, asbestos, aluminum oxide, and silicon dioxide [16].

Nano-enhanced polymers. Research indicates that polymer nanocomposites enriched with clay, carbon nanotubes, and other nanomaterials not only improve fire resistance but also enhance mechanical properties. During combustion, a protective char layer forms on the surface, which reduces heat transfer and limits flame spread.

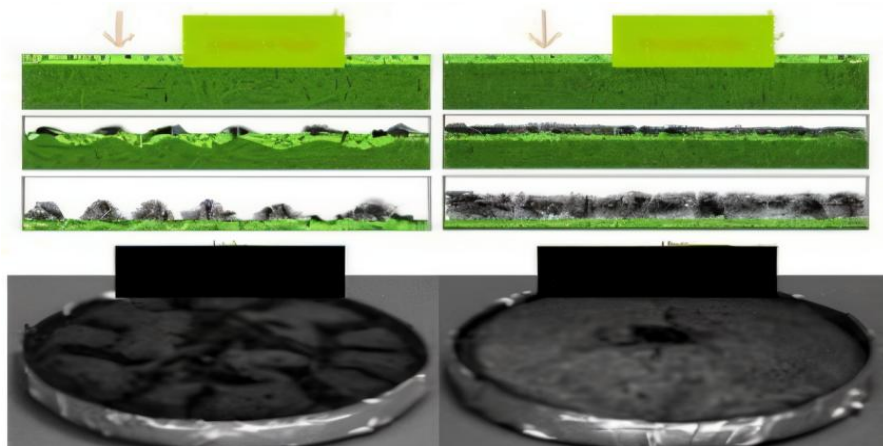


Fig. 3. The image illustrates the operating mechanism of nano-enhanced flame retardants [16].

Figure caption. Structure of flame-retardant coatings: The left and right sides depict the composition of different flame-retardant materials. The green areas in the upper layers represent polymer materials stabilized with fire-resistant additives, while the black and white layers below are char layers formed as a result of heat exposure. It has been demonstrated that the protective char layer formed due to nanoadditive flame retardants is structurally more stable. The effectiveness of the protective char during combustion is attributed to the black sublayer. As seen

in the right-hand image, polymers with nano-additives form a denser and more robust char layer, which limits heat transfer and insulates the underlying material.

Circular images below: The left image shows that polymers without nano-additives form an irregular and fragmented char layer when exposed to heat. The final image on the right demonstrates that nano-enhanced polymers produce a denser and more uniform protective coating when burned.

The protective char layer shields the base material from oxygen and heat, thereby preventing the spread of flames. In terms of application, flame-retardant polymers are used in the production of construction materials, automotive components, and electrical parts [16].

2.4. Application of nanomaterials in construction: advantages and limitations

Advantages:

- Improved energy efficiency – aerogel-based nano-insulation materials reduce heat loss by approximately 60% compared to conventional materials. This significantly reduces energy consumption in buildings.
- Self-cleaning process – facade coatings with TiO₂ nanoparticles effectively decompose organic pollutants on their surface under UV light.
- Corrosion protection – nanocomposite coatings reduce the corrosion rate of metal structures [1].

Limitations:

- Economic considerations – the production of nanomaterials is 4–5 times more expensive than conventional materials. This limits their application, especially in small and medium-sized projects.
- Production challenges – the manufacture of high-quality nanoparticles requires advanced equipment and highly skilled specialists.
- Health risks – inhalation exposure to nanoparticles can lead to pulmonary fibrosis. This necessitates additional protective measures for workers in the construction industry.
- Environmental impacts – additional safety measures are required to ensure the welfare of workers in the construction sector [1].

3. Conclusion

Studies show that when nanoparticles are added to various materials, their mechanical strength, environmental compatibility, and durability increase. In particular, the application of substances such as TiO₂, ZnO, WO₃, graphene, and carbon nanotubes has led to innovative changes in concrete, steel, and insulation systems.

At the same time, approaches based on biological mechanisms (e.g., experiments with *Bacillus* species and *Trichoderma reesei*) reveal the bio-integrative potential of nanotechnology.

However, the large-scale application of these technologies faces certain limitations. The high production costs of nanomaterials, their toxic potential, and environmental impact issues require the development of future research and regulatory frameworks.

As a result, the use of nanotechnology in the construction industry has become a strategic tool that can determine the future trajectory of this field. For this, both the continuity of scientific research and the maintenance of economic and environmental balance in industrial applications are essential.

The present study highlights the substantial impact of nanotechnology on modern construction materials, demonstrating both functional and durability enhancements. Key conclusions are summarized as follows:

- **Mechanical and functional improvements:** The incorporation of nanoparticles into concrete, steel, polymers, and insulation materials significantly enhances mechanical strength, water and corrosion resistance, as well as thermal insulation performance.
- **Bio-integrative potential:** Self-healing concrete technologies, utilizing *Bacillus* species and *Trichoderma reesei*, confirm the capability of nanotechnology to integrate with biological systems, prolonging structural service life and reducing maintenance requirements.
- **Innovative safety and efficiency solutions:** Nano-enhanced polymers and fire-resistant materials provide advanced solutions for improving building safety and energy efficiency.
- **Challenges and limitations:** The large-scale adoption of nanomaterials is constrained by economic considerations, potential health risks, and environmental impacts, highlighting the need for robust regulatory frameworks and continued research.
- **Strategic significance:** Overall, nanotechnology emerges as a strategic tool in modern construction, offering considerable potential to improve technical performance, durability, and environmental sustainability in industrial applications.

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