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Enhancing Fire Protection in Buildings Using Nanotechnology

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Nanotechnology is a recent innovation that has changed many fields of construction and engineering, especially concerning fire protection in high-rise buildings. Conventional building materials can be significantly enhanced in terms of fire protection by taking advantage of the unique molecular properties of nanoparticles. Nanotechnology has become an important tool in improving the safety and protection of buildings, especially against fire hazards, which is one of the most difficult tasks faced by architects and civil engineers. This paper provides a comprehensive analysis of the latest advancements in nanomaterials for fire protection, comparing their effectiveness with conventional fire-resistant materials and discussing their economic and environmental benefits.

Keywords: Nanomaterials- protecting buildings – fire Protection.

1. Introduction

Nanotechnology has transformed various industries, including building and civil engineering, particularly fire protection. Nanomaterials improve the performance of traditional materials by utilizing their unique molecular characteristics to increase fire resistance. Fire resistance in buildings is an increasing topic since it is critical for fire response and evacuation. Fire protection refers to efforts that safeguard life, health, property, and the environment from fire and its repercussions[i]. Protection methods cover fire prevention and people and property safety in an emergency.[ii] Variables such as fire resistance, material durability, structural strength, smoke release, and toxicological dangers in building materials are crucial in safeguarding residents and giving them a higher chance of escape and survival in the case of a fire.[iii] However, many manufacturers design items to maximize revenues, which includes adopting lighter, thinner materials, regardless of flammability.[iv] In addition to using lighter, thinner, and less fire-resistant materials, certain flammable materials are used in building construction, such as outside heat insulation panels and phase change materials for cooling buildings, prompting many researchers to seek novel solutions to this growing problem.[v]

This study looks at how nanotechnology can improve fire protection systems in buildings. The study examines the function of nanomaterials in increasing building fire resistance through

new technologies that help mitigate the impacts of fire on structural structures and interior components. It also intends to investigate the physical and chemical features of nanoparticles that make them efficient in fire prevention and compare their efficacy to traditional materials utilized in this sector. The research fills a gap by examining several nanomaterials and their practical use in fire-resistant building. It also includes practical and inventive solutions for improving building safety, achieving sustainability, and reducing environmental impact.

2. Methods

This research is based on a comprehensive examination of the literature review, a comparative material analysis, and actual case studies. Data from research studies on nano-enhanced fire-resistant materials were collated and analyzed to evaluate their performance under various scenarios.

3. Application of Nanomaterials in Fire Protection

Nanotechnology is the development and application of functional structures with at least one characteristic dimension measured in nanometers. Just how small is a nanometer? To put that into perspective, the average width of a human hair is 50 micrometers. A micrometer is the same length as 1000 nanometers. In conclusion, one nanometer is 50,000 times smaller than a human hair. Working with technology on such a small scale enables scientists to improve physical, chemical, and biological qualities drastically. Activity at the nanoscale may be less predictable than at the larger scale.[vi,vii] Nanotechnology has the potential to provide unprecedented insight into the inner workings of objects and have a positive impact on a wide range of industries. For example, switching devices and functional units at the nanoscale can dramatically enhance computer storage. New biological sensors can identify cancer at an earlier stage. Nanotechnology is particularly important in the realm of engineering.[viii]

4. Nano-treated concrete.

Concrete is the most common and frequently utilized building material in the construction industry, as it is used to construct the structure's structural frame with other materials. It is one of the materials treated with nanotechnology in various ways[ix], There are various ways to incorporate nanotechnology into concrete that will greatly improve its desirable properties, such as durability, strength, flexibility, and cleanliness[7].

4.1 Concrete treated with carbon nanotubes.

Carbon nanotubes send electrical signals at levels where regular current cannot flow thanks to a quantum feature known as electron tunneling. Because of their design flexibility, carbon nanotubes also function as semiconductors. Carbon nanotubes have been utilized as tiny wires to join disparate computer parts.[x] In addition to their special electrical characteristics, carbon nanotubes are known for their exceptional strength and endurance, which can be used to significantly enhance the qualities of fibers and other materials when added in trace amounts.[xi] Carbon fibers are also known for neither corroding nor burning under normal conditions,

except at extremely high temperatures.[xii] They can be added to the concrete mixture by replacing some of the cement with carbon fibers. The optimal percentage for adding carbon fibers is 1%, with a superplasticizer of 4%, because adding carbon fibers to the concrete mixture alters its workability, necessitating the addition of superplasticizers (SP) to increase the softness of the concrete.[xiii]

4.2 Transparent Nano Concrete

Concrete transmits light from the outside to the inside, transforming the structure into a huge window. It is made of transparent thermoplastic resin and inorganic materials such as concrete, through which light passes. Nanotechnology has improved the qualities and features of materials.[xiv] It is a fire-resistant material that excellently insulates heat and sound. It can be easily handled as it can be manufactured according to the required specifications and with a specific strength and density. Its quality can also be controlled. It also resists different conditions as it has low moisture absorption. It gives the building an aesthetic appearance at night due to the appearance of lighting from the inside to the outside.[xv] During the day, it gives a reflection of the surrounding environment. This technology has been used in designing architectural facades to become similar to a large window that allows sunlight to pass into the interior spaces during the day. Less internal lighting is used, which leads to saving energy consumed. It is characterized by being light in weight in prefabricated parts, and it is inexpensive compared to other materials. The percentage of light transmission through a wall with a thickness of 5 cm has reached 20%.[xvi]

4.3 Glass Fiber Reinforced Concrete

It is a type of concrete that combines fine sand, cement, polymer (often acrylic polymer), water, additional additives, and alkali-resistant fiberglass. The qualities of GFRC vary according on mix design, glass content, and manufacturing techniques. GFRC uses fiberglass, which has a stronger tensile strength than steel. In general, the larger the fiber concentration, the stronger the material. One advantage of GFRC is that it is fire-resistant because it is made of metal and does not burn. Furthermore, the nature of concrete functions as a thermostat, and when exposed to a flame, GFRC not only does not burn but also protects the materials behind it from the flame's heat.[xvii] To increase the commercial potential of lightweight materials used in structural construction, GFRC is treated with nanotechnology. The additive containing nanomaterials improves foam-based GFRC materials' fire retardancy for at least three hours. This invention helps to improve strength and flame retardancy, and the benefits of Nano GFRC are as follows:[xviii]

a) Makes foam-based building materials more flame-resistant.

b) Significantly lower emissions of harmful gases during fire.

c) Improves the construction materials' structural performance.

Nanomaterial additives increase the fire resistance of foam-based GFRC materials by at least three hours. Right now, it has a 15-minute rating. Although standards now only permit the use of foam-based GFRC for non-structural walls, with higher ratings, the material might be utilized for all of the structural components of both residential and commercial structures. It has a major impact below the nanoscale scale[xix],And Table 1 show Fire Resistance of Nano-Treated Concrete vs. Conventional Concrete.

Material	Fire Resistance Time	Structural Integrity	Thermal Conductivity
Conventional Concrete	1 hour	Moderate	High
Carbon Nanotube Concrete	3 hours	High	Low
Transparent Nano Concrete	3 hours	High	Low
Nano GFRC	3 hours	Very High	Low

Table 1: Fire Resistance of Nano-Treated Concrete vs. Conventional Concrete (Researcher work)

5. Fire-resistant finishing materials

As nanotechnology advances building materials, it also advances finishing materials, giving them new qualities that satisfy a wider range of customer requirements, such as:

5.1. Nano-treated glass

Glass is one of the most important materials used in building finishing today, whether on the exterior or the interior, and nanotechnology has been used in glass, impacting its attributes such as fire resistance.[xx]

It has become one of the most important materials used to resist fire because it comprises several sheets with transparent layers of various materials between them. When the glass is exposed to fire, the panel facing the flame cracks, but it remains in place, and the layers combine to form a thick foam that insulates against fire. Ordinary glass can tolerate temperatures below 100 degrees Celsius before shattering, however, nanotechnology-treated glass can withstand temperatures about 260 degrees Celsius, Heat-resistant glass can endure (2500:3000) degrees Celsius, allowing it to withstand fires for up to 120 minutes while preventing them from spreading to adjacent floors, staircases, and places.[xxi]

5.2. Nano-plastic wood

Wood is one of the most commonly used materials in construction and finishing, therefore applying nanotechnology in wood results in nano-plastic wood, which blends wood and plastic elements. This material is utilized for a variety of applications, including simple construction and interior finishing like accessories and decorations.[xxii] Its molecules have been collected and rearranged, making it more cohesive and stronger than the natural substance, as well as possessing additional and superior qualities. One of its most essential characteristics is its resistance to fire and extreme temperatures. When exposed to high temperatures caused by flames, nano-plastic wood resists heat and does not ignite, as opposed to natural wood, which burns and goes to ash.[xxiii]

5.3. Nano-treated foam

When the foam is treated with nanotechnology and the makeup of the material's molecules is

adjusted, it becomes resistant and fire-retardant. When exposed to fire, it does not burn or change into a liquid, unlike regular foam.[xxiv] Nano-treated foam is one of the greatest fire-resistant materials since it extinguishes itself when exposed to fire and emits no hazardous elements. It's an environmentally friendly substance.[xxv]

5.4. Fire-resistant nano vacuum insulation panels

They are nanotechnology-treated insulating panels that are fire and heat-resistant, with an insulation capacity six times that of ordinary insulating materials. Because of their relatively thin thickness, these panels are employed in ceilings as well as internal and external walls, saving 10% of the building area used[xxvi,xxvii] ,And Fig 1 show, Fire resistance time of nano-treated glass, nano-plastic wood, and conventional materials.

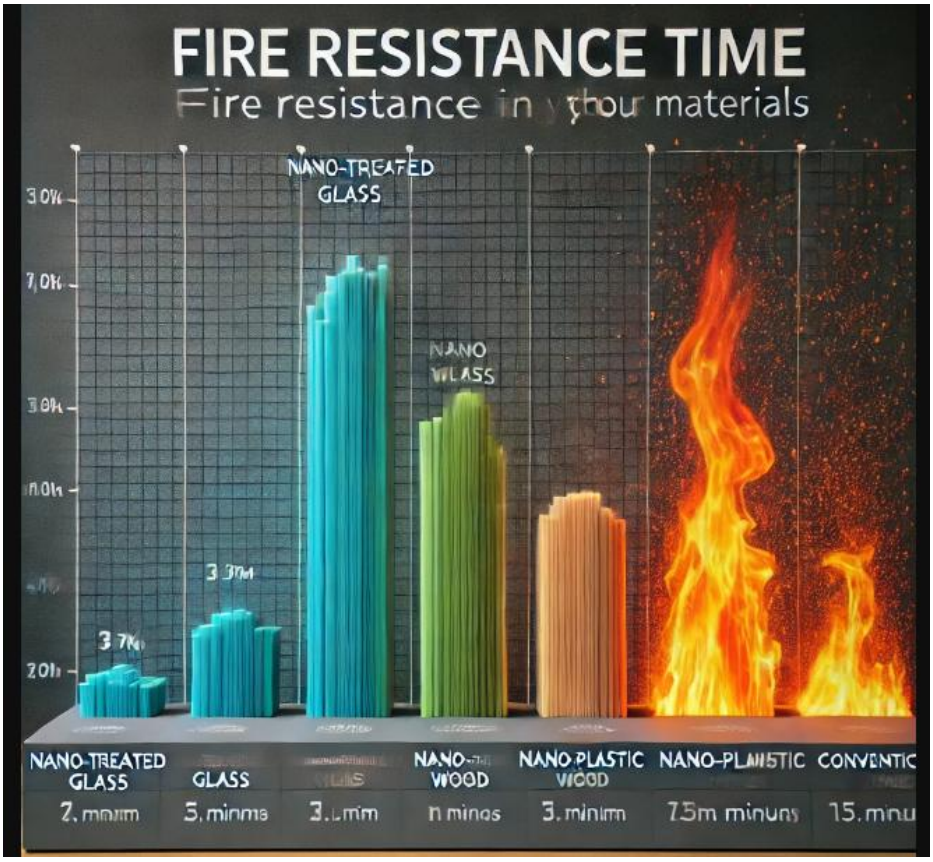

Fig 1 show, Fire resistance time of nano-treated glass, nano-plastic wood, and conventional materials. (Reference: Generated using comparative data from literature and computational analysis.)

And Table 2 show Comparison of Fire-Resistant Finishing Materials:

Material	Fire Resistance Time	Key Properties
Nano-Treated Glass	Up to 120 minutes	Multi-layered, heat-insulating foam
Nano-Plastic Wood	High	Fire-resistant, durable, non-igniting
Nano-Treated Foam	Self-extinguishing	No toxic emissions, eco-friendly
Nano Vacuum Insulation Panels	6x insulation capacity	Thin, space-saving, fire-resistant

Table 2 show Comparison of Fire-Resistant Finishing Materials (Researcher work)

6. Nano coatings

Nanomaterials used in the manufacture of nano paints are magnesium oxide, copper oxide, cerium dioxide, aluminum, zinc oxide, silicon dioxide, and others. A variety of nanomaterials, including silicon dioxide, magnesium oxide, copper oxide, cerium dioxide, aluminum, and zinc oxide, are utilized in the production of nano paints. Nano paints are created by mixing these substances.[xxviii] The nanoparticles in nano paints allow them to retain characteristics that ordinary paints do not. To allow the paints to breathe, ventilation is applied to their surfaces. After being sprayed with nano, we discover that the walls can breathe and discharge vapors.[xxix]

Because nano paints don't clog the pores of walls and partitions, the vibrant surroundings no longer contaminate the air and become good for us. As a result, there are no symptoms of rot or cracking of the walls from the lack of water evaporation. In addition, it has antimicrobial qualities, is free of volatile compounds, and has qualities that protect against fire, heat insulation, and scratches. As a result, its use is deemed safe and healthful. Since it is thought to be the best for wall paints, its use is therefore essential.[xxx]

6.1. Nano Coating to Protect the Metal Structure from Fire

It is a coating made by combining cementitious materials and carbon nanotubes to create compounds with unique qualities that are applied in a variety of industries. Because the polypropylene fibers in the carbon tubes give the material more strength and resistance, this coating is used on metal structures (Steel Structure System) to increase fire resistance.[xxxi] It is also a great alternative to traditional insulation because it is less expensive. When this coating is placed on metal structures, it becomes highly fire resistant in addition to the other benefits that the nano characteristics provide, such as pressure resistance, self-cleaning, and many more.[xxxii]

6.2. NANODECK Wood Fire Protection Coating

It is a Nano coating for solid wood, plywood panels, and wood veneers used in interior design. This coating is unique because it is odorless, free of halogens, heavy metals, and solvents, easy to clean, roll, and spray, and transparent (colorless). The Nano deck coating is a fire-resistant coating because it acts as an insulator, protecting wood panels from flames by generating a heat-insulating foam layer of carbon that can be scraped off the outside surface and leaves no

evidence of fire.[xxxiii]

6.3. Nano Silica Coating Protects the Glass from Fires

It is a transparent coating applied to glass. When exposed to fire, this layer, made up of nanoparticles of silica dust (Sio2), transforms into a transparent fire shield that protects the glass from flames. When heated further, it produces a foamy substance that acts as a heat insulation layer. This is because fire coating can minimize heat transfer, and it has been utilized on glass in many buildings' external facades.[xxxiv]

6.4. Nano Ceramic Coating for Ceramic Tiles

Using nanotechnology to treat ceramic tiles with transparent nano ceramic coatings results in a multi-functional surface with properties such as fire and flame resistance, scratch resistance, anti-bacterial, increased durability and strength, flexible formability, and ease of cleaning (self-cleaning, water and dirt repellent).[xxxv] When the ceramic treated with a nano-ceramic coating is exposed to flames, it functions as a fire insulator for the tile, and once the fire is out, it can be cleaned and the ceramic tile returns to its former shape.[xxxvi] Ceramic tiles treated with nano-ceramic coating were utilized in interior finishing for ceramic floors and walls, as well as in external facades to provide an appealing look and non-static dynamism to the building's external formation.[xxxvii]

6.5. Nano Coating to Protect Furniture and Furnishings

Nanotechnology has been used in the production of coatings and insulating materials that are used in homes, residential units, offices, and buildings that contain furniture and furnishings to protect them from fires. Nano coating is a transparent coating that is applied to furniture, carpets, and curtains to make them fireproof or water resistant. This coating is one of the most important products of nanotechnology, as when studying the causes of fires and the places that ignite the most quickly when a fire breaks out, it became clear that furniture and furnishings are the most engulfed by flames due to their rapid ignition (because most, if not all, of the contents of furniture and furnishings, are highly flammable cotton products).[xxxviii] When applied, this coating protects the contents of buildings from the major threats of fire. These textiles are occasionally impregnated with the coating, which is made of environmentally benign materials (odorless, devoid of halogens, heavy metals, and solvents) and is simple to apply (by impregnation or spraying).[xxxix] This paint is most commonly used inside residential buildings since it contains many flammable furniture and fabrics, followed by administrative buildings, furniture and textile stores, and many other structures[xl], And Table 3 show Comparison of Nano Coatings for Fire Protection

Material	Fire Resistance Time	Key Properties
Coating Type	Application	Key Properties
Nano Coating for Metal Structures	Steel structures	High fire resistance, cost-effective
NANODECK Wood Fire Protection Coating	Solid wood, plywood	Transparent, solvent-free, easy to apply
Nano Silica Glass Coating	Glass surfaces	Heat-insulating, foam-forming shield

Nano Ceramic Coating	Ceramic tiles	Fire-resistant, scratch-proof, antibacterial
Nano Coating for Furniture & Furnishings	Fabrics, carpets, curtains	Fireproof, water-resistant, eco-friendly

Table 3 show Comparison of Nano Coatings for Fire Protection (Researcher work)

7. Advanced Performance Metrics and Fire Resistance Measurement

A Fire Performance Scale has been created in order to standardize the evaluation of nanomaterial fire resistance, and Table 4 show standardize the assessment of nanomaterial fire resistance, a Fire Performance Scale:

Fire Resistance Class	Temperature Resistance (°C)	Time Endurance (minutes)	Structural Integrity Retention
Low Resistance	< 300°C	< 30 min	Weak
Moderate Resistance	300-600°C	30-90 min	Moderate
High Resistance	600-900°C	90-180 min	Strong
Ultra-Resistance	> 900°C	> 180 min	Very Strong

Table 4 show standardize the assessment of nanomaterial fire resistance, a Fire Performance Scale (Researcher work)

8. Fire Resistance Scale

8.1.Rating from 1 to 5, where 5 represents the highest performance level ,and Table 5 show Rating from 1 to 5, where 5 represents the highest performance level:

Material	Fire Resistance (1-5)	Durability (1-5)	Environmental Impact (1-5)	Cost Efficiency (1-5)
Conventional Concrete	2	3	3	4
Carbon Nanotube Concrete	4	5	4	3
Transparent Nano Concrete	4	5	4	3
Nano GFRC	5	5	5	3
Nano-Treated Glass	4	4	4	3
Nano-Plastic Wood	3	4	4	4

Nano-Treated Foam	4	3	5	4
Nano Vacuum Insulation Panels	5	5	5	2
Nano Coating for Metal Structures	5	5	4	3
NANODECK Wood Fire Protection Coating	4	4	4	4
Nano Silica Glass Coating	4	4	5	3
Nano Ceramic Coating	5	5	5	3
Nano Coating for Furniture & Furnishings	4	4	5	4

Table 5 show Rating from 1 to 5, where 5 represents the highest performance level (Researcher work)

8.2. Evaluation Scale for Nano-Treated Materials in Fire Protection, as shown in Table 6 Evaluation Scale for Nano-Treated Materials in Fire Protection:

Criterion	Low (1)	Medium (2)	High (3)
Fire Resistance	< 1 hour	1-2 hours	> 3 hours
Structural Integrity	Weak	Moderate	Strong
Thermal Conductivity	High	Medium	Low
Eco-Friendliness	Toxic emissions	Reduced emissions	Non-toxic
Cost-Effectiveness	Expensive	Moderate	Affordable
Ease of Application	Complex	Moderate	Simple

Table 6 show Evaluation Scale for Nano-Treated Materials in Fire Protection (Researcher work)

This comprehensive study offers a transparent evaluation of nanomaterials' fire safety capabilities, enabling well-informed material selection for building and finishing applications.

9. Economic and Environmental Impact

The use of nanotechnology in fire protection presents several economic and environmental advantages:

- Cost Efficiency: Despite the initial cost, nano-enhanced materials reduce maintenance expenses and structural damage repair costs.
- Environmental Sustainability: Lower emissions of toxic fumes, improved recyclability, and enhanced durability contribute to green building initiatives.

And table 7 show Cost-Benefit Analysis of Nano Fire-Resistant Materials

Material	Initial Cost	Maintenance Cost	Lifespan	Sustainability Rating
Traditional Fireproofing	Low	High	~10 years	Moderate
Nano-Coated Fireproofing	Moderate	Low	~25 years	High

Table 7 show Cost-Benefit Analysis of Nano Fire-Resistant Materials (Researcher work)

10. Results and Discussion

The results of this study demonstrate that nanotechnology has transformed fire protection in construction by significantly enhancing the mechanical properties, durability, and fire resistance of traditional materials. Nanomaterials such as nano-silica and nano-carbon improve concrete strength, reducing cracking and corrosion, while nano-metal oxides in fire-resistant coatings effectively reduce material flammability, slow fire spread, and protect structures from high-temperature damage.

Furthermore, the integration of nanoparticles has enabled the development of lightweight yet high-performance structures, supporting the construction of taller, more resilient, and more sustainable buildings. Nano-coating layers enhance thermal insulation, reducing building energy consumption while simultaneously improving fire resistance.

Fire Resistance Classification and Performance Evaluation

A Fire Performance Scale was developed to evaluate nanomaterials based on temperature resistance, endurance time, and structural integrity retention. The findings indicate that nano-enhanced materials significantly outperform conventional materials:

- Nano Glass Fiber Reinforced Concrete (Nano-GFRC), Nano Ceramic Coating, and Nano Vacuum Insulation Panels exhibited high fire resistance and strong structural retention under extreme heat conditions.
- A rating system from 1 to 5 was used to assess fire resistance, durability, environmental impact, and cost efficiency, where nano-enhanced materials consistently achieved higher ratings than traditional fireproofing solutions.
- Nano-treated materials withstand over 3 hours of fire exposure, maintain strong structural integrity, and emit fewer toxic substances, making them a more eco-friendly choice for fire protection.

Economic and Environmental Considerations

Beyond fire safety, nanotechnology plays a crucial role in environmental sustainability by reducing toxic emissions and enabling the effective recycling of burned materials. A cost-benefit analysis revealed that:

- Nano-coated fireproofing materials last approximately 25 years, compared to 10 years for conventional fireproofing, reducing the need for frequent maintenance.
- Maintenance costs are significantly lower, making nano-materials more cost-effective in the long run despite their higher initial investment.
- The sustainability ratings of nano-materials support green building initiatives, contributing to energy efficiency, material recyclability, and reduced environmental impact.

11. Conclusions

This study confirms that nanotechnology is not only a tool for improving construction quality but also a key factor in achieving safer, more sustainable, and cost-efficient buildings. Nano-enhanced fire-resistant materials offer improved fire resistance, durability, and eco-friendliness, proving to be superior alternatives to traditional materials.

To facilitate the widespread adoption of nanotechnology in fire-resistant construction, future research should focus on:

- Large-scale applications to assess the feasibility of mass implementation.
- Computational modeling of fire resistance to optimize material properties.
- Regulatory frameworks and safety standards to ensure compliance and widespread acceptance.

By addressing these challenges, nanotechnology can become a cornerstone of fire-resistant construction, offering long-term cost savings, enhanced safety, and environmental sustainability.

• Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

• Competing interests

The authors declare that they have no competing interests

• Funding

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• Authors' contributions

AE designed the research study, conducted data collection and analysis, and drafted the manuscript. MS and TN contributed by providing valuable feedback, revising the manuscript, and approving the final version for submission.

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