Advances in Nano Research, *Vol. 18, No. 3 (2025) 281-288*
https://doi.org/10.12989/anr.2025.18.3.281

Effects of nanotechnology in the structural innovation of modern architecture structures and improving the energy efficiency

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(*Received January 1, 2025, Revised February 20, 2025, Accepted March 5, 2025*)

Abstract. Nanotechnology has been integrated into architectural design, and the construction industry is experiencing new solutions that give better structural integrity, aesthetic value, and sustainability for buildings. This paper elaborately analyses and creates, with a lot of care and imagination, the use of nanotechnology in engineering resistant architectural structures linking innovation in scientific research to the artistic principles of designs. Nanotechnology, through the manipulation of materials at the nanoscale level, provides a variety of prospects that will extend or even redefine conventional construction methods for architects and engineers. Architectural structures with precisely constituted nanomaterials—carbon nanotubes and graphene derive strength and resilience unprecedented in their ability to withstand environmental stresses and human impacts. This approach is not bereft of the artistic aspect in architectural design, even if it has a technologically zealous name. Using nanomaterial properties, an architect can let his imagination run wild and pull out architecturally striking, avant-garde structures that set the imagination afire while serving practical purposes. This will offer an avenue for the fusion of art and science in the design process to unleash new ways of iconic landmark creation testaments which shall reflect human ingenuity and progress. It will, therefore, be seeking to explore the multi-dimensional applications of Nanotechnology in terms of architecture, ranging from structural analysis to aesthetic improvement and sustainability with durability. It is the belief of the paper that in pointing out or highlighting the symbiotic relationship that exists between technology and artistry, it will be in a position to segue the community of architects to be more innovative, experiment with new ideas in the architectural design dimension.
Keywords: architectural structures, artistic design, nanotechnology, sustainability for buildings

1. Introduction

Architecture today uses technology coupled with creativity, spans new heights of innovation, and beauty. One such exciting development in this field is nanotechnology. This advanced technology associated with manipulating materials on an incredibly small scale is revolutionizing the way designs are made and buildings constructed. It's not just about the ability of making buildings stronger and more resilient against all odds, rather, it's about making them as beautiful as they can be functional.

Imagine a skyscraper that could stand up against earthquakes and harsh weather, sleek in its own right. Or maybe a home that stays cool in summer and warm in winter, using materials that are as energy-efficient as they are environmentally friendly. That is what nanotechnology does for architecture. Combining tiny but remarkably powerful materials into their designs assists architects and engineers to build more durable, efficient, and inimitable structures to the eye than ever before. There are many works for structures such as Gao *et al*. (2022), Zhang *et al*. (2023b), Huang *et al*. (2021) and Wu *et al*. (2023).

The real magic of nanotechnology lies in its ability to alter the very foundations of our world (Tan *et al*. 2020, Zhang *et al*. 2022a, Daikh *et al*. 2023, Berghouti *et al*. 2019). It is unimaginable what can be done to the properties of materials through dealings at a nanoscale level: advance, stronger steel, resilient concrete, and self-cleaning glass. Such developments not only account for extended life spans with efficiency for buildings but also a completely new perspective toward creative expression. It is within the capacity of architects to play around with shapes, textures, and forms in trying to come up with designs of structures to increase frontier possibilities or become iconic buildings that usually turn out to be great testimonies of human ingenuity. Adibi and Talebkhah (2022) studied seismic response assessment of the concrete precast buildings. Amezcua and Ayala (2023) presented a computationally numerical efficient method for non-linear FEM strain practical applications based on one-point constitutive theory. Tayebi *et al*. (2023) studied free vibration response of composite FG plates with nanoparticles exposed to thermal load. Shu *et al*. (2023) investigated the new moment-resisting glulam beam-to-column connection reinforced with long self-tapping screws and long steel rods screwheads. Liu *et al*. (2024) and Ji *et al*. (2024) presented and analysis mathematical modeling of the rolled tailor blank manufacturing procedure.

It's not about the buildings on their own. Nano-technology contributes much to making construction more

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ISSN: 2287-237X (Print), 2287-2388 (Online)

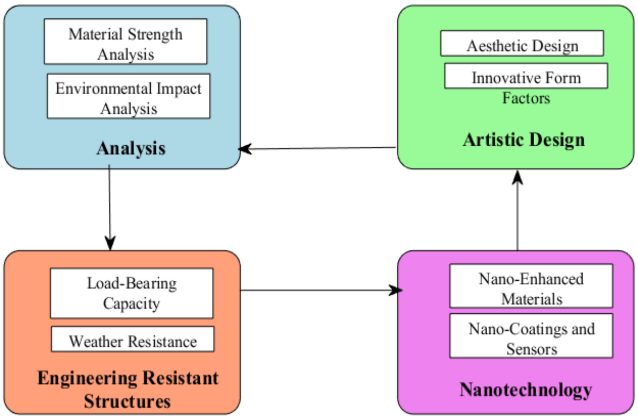

Fig. 1 A schematic figure of integrating nanotechnology into analysis and artistic design for engineering-resistant architecture

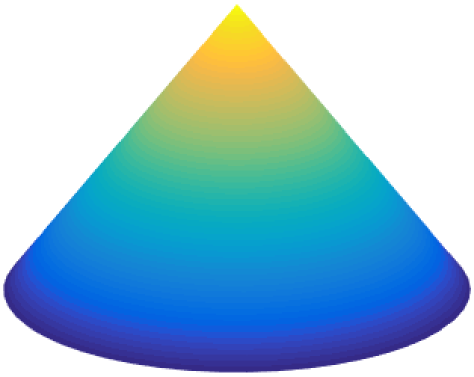

Fig. 2 The schematic of conical shells in architectural structures

sustainable. We lessen our ecological footprint by reducing the use of heavy, resource-consuming materials and increasing energy efficiency. This becomes very imperative as we move into a more sustainable future. Tian *et al.* (2023) investigated energy absorption and dynamic crushing analysis of auxetic hybrid metamaterial by motif Islamic art.

This paper is going to look into how nanotechnology creates resilient architectural structures that at the same time are works of art. We shall consider specific examples of nanomaterials and techniques and how they are transforming the preference towards designing and constructing. A look into how technology is married to creativity in the opening of a new Age of Architecture: one in which beauty aligns effortlessly at one and the same time with strength and sustainability.

2. Artistic design

Below is a schematic figure (Fig. 1) of integrating nanotechnology into analysis and artistic design for engineering-resistant architecture. The graphical representation illustrates the interlocking components that go into making an architectural design beautiful and strong in this cutting edge creation.

A- Analysis: This module gives emphasis on Material strength analysis and Environmental impact analysis to make sure that the materials chosen can sustain all kinds of stressors and also contribute positively towards the environment.

B-Artistic Design: This is that part of the design that writes about esthetics, breaking right through the form factor to develop structures that are most please able to the eye but have a number of innovative design kinds integrated.

C-Structures Resistant to Impact and Weather: This is the section for load-bearing capacity and weather resistance, ensuring that structures can sustain physical and environmental challenges.

D-Nanotechnology just stands for the use of nano-enhanced materials and nano-coatings and sensors, using high-tech technological measures to improve performance and durability characteristics of these kinds of structures.

The arrows show a flux and relation between these elements: each one contributes to the comprehensive design and analysis of engineering-resistant architectures with the help of nanotechnology (Xie *et al*. 2025, Hao *et al*. 2024, Zhang *et al*. 2023b).

2.1 Analysis of nanomaterials in architecture

Nanomaterials have many advantages over traditional construction materials. For example, carbon nanotubes are well known to have high strength and elasticity, hence, they can be very useful concrete and steel reinforcement materials. Nanocomposites, a mixture of nanoparticles and traditional materials, may highly enhance a lot of kinds of properties, like thermal resistance, electric conductivity, mechanical strength, and so on. Almost nano-coatings have the potential to enhance self-cleaning, anti-corrosion properties, and UV resistance attributes on the surface, which in turn decrease the cost of maintenance and increase the lifetime of the structure (Ma *et al*. 2019, Gong *et al*. 2024, Zhang *et al*. 2022b, Cheng *et al*. 2023).

In order to study the effect of nano-materials on the architecture structures, presentation of mathematical modeling and analytical solution is essential. As shown in Fig. 2, conical shells offer large aesthetic benefits, allowing the architect to create visual effects and iconic constructions. Fluid, dynamic forms of architecture realize a good possibility of unique expression, standing out in an urban landscape. For instance, the possibility is given by conical shapes for the landmark or iconic building to define the silhouette of a city. Second, this flexibility of conical shell geometry allows a wide range of designs to be made-from futuristic buildings to structures inspired by nature.

The energy relations for the structure:

$$U = \frac{1}{2}\int \sigma_{ij}\varepsilon_{ij}dV \quad (1)$$

$$K = \frac{\rho}{2}\int (\dot{u}^2 + \dot{v}^2 + \dot{w}^2)dV, \quad (2)$$

$$W = \int fwdA \quad (3)$$

where σ_{ij} is the stress, ε_{ij} is the strain, $(\dot{u}^2, \dot{v}^2, \dot{w}^2)$ are the velocity in three directions, ρ is the density and f is the force. With the help of Hamilton's principle as:

$$\int_0^t (\delta U - \delta K - \delta W)dt = 0 \tag{4}$$

we have:

$$[M][\ddot{Y}] + [K][Y] = [0], \tag{5}$$

in which [K] is the stiffness and [M] is mass matrixes.

2.2 Artistic design with nanotechnology

Nanotechnology has enormous aesthetic promise in the field of architecture. In the long term, nano-engineered materials will make it possible to engineer their interaction with light in particular ways and engender surfaces that change either in color or transparency, depending on changing environmental conditions. Therein, architects have the ability to design buildings that are dynamic and responsive to their setting while enhancing functionality and aesthetic value.

Research in the field of nanotechnology involves the extremely accurate development of material properties with regard to their size, shape, and composition at scales smaller than the wavelength of light. In this way, it allows for the opening to nanostructures exhibiting unique optical, mechanical, and electrical properties with very far-reaching diversified applications in areas as wide-ranging as electronics, medicine, and sustainable energy. For example, the interactions of nanoparticles with light at different wavelengths can be designed to interact with their color and reflectivity, much like pigments in traditional artistic media.

With respect to the relation of stress and strain as:

$$\sigma = C\varepsilon \tag{6}$$

and this point that C is the elastic constant, the effect of nanoparticles can be assumed by mixture method as:

$$C = C_m V_m + C_n V_n \tag{7}$$

where V_m and V_n are the volume percent of matrix and nanoparticle.

2.3 Engineering-resistant structures

The resistant structures are specialized designs of buildings, bridges, and infrastructure that take durability, resilience, and safety as priorities against environmental and operational challenges posed to them. This engineering discipline unites the most advanced materials with novel design principles, having well-developed test methodologies that ensure such structures can survive extreme conditions and withstand unexpected events.

The very simplest of resistant structures, at their simplest, are designed for better living, making use of extremely solid materials such as high-strength concrete, steel alloys, and composite materials. They are used because of their resilience against corrosion, fatigue, and mechanical stress, hence increasing the life of the whole structure while reducing maintenance costs. Besides, state-of-the-art technologies including advanced modeling and simulation tools will enable engineers to optimize structural designs against environmental loads, seismic activity, wind forces, and other potential hazards.

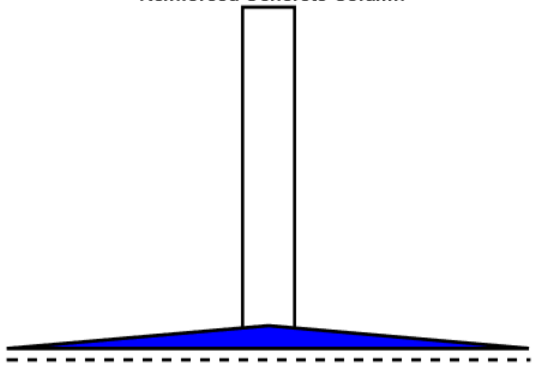

Fig. 3 A schematic of engineering-resistant structures

Fig. 3 has been prepared to show the philosophy behind Engineering-Resistant Structures. This figure represents various aspects of design showing resilient materials and new design methodologies, with emphasis on stability and structural safety. Elements such as reinforced concrete columns, steel trusses, and protective coatings are used to signify the concept of solidity and durability inbuilt into the irritation-resistant methods of construction. Further, this conveys the idea of constant monitoring and maintenance checks at regular intervals to ensure its entity throughout service life.

3. Results and discussion

Applied to architecture, nanotechnology is one very promising path for resilient artistic buildings. This paper considers discussions on different case studies about the applications of nanoparticles or nanomaterials applied for practical and additional benefits in architectural engineering. Accompanying problems in terms of cost and special knowledge and apparatus needed after their adoption are brought with advantages that these technologies bring. If nanotechnology is to realize its full potential in architectural structures, further papers and development in this field is essential to function beyond these barriers.

Table 1: Some mechanical properties of A, B and C nanocomposites used in engineering-resistant sustainable architectural structures, features burging—tensile strength, flexural modulus, impact resistance, self-c cleaning ability, and energy efficiency. Nanocomposite B is highest in tensile strength and flexural modulus, thereby sustaining load very well. Nanocomposite A has the highest value for impact strength. Nanocomposite C is quite efficient, with improved impact-resistant and enhanced insulation properties that will improve durability, hence better energy performance in their application to architectural building.

Table 1 Mechanical data of nanotechnology-improved materials

Material Type	Tensile Strength (MPa)	Flexural Modulus (GPa)	Sustainability Features
Nanocomposite A	450	35	Self-cleaning, Energy-efficient
Nanocomposite B	400	30	High thermal insulation
Nanocomposite C	500	40	Lightweight, Durable

Table 2 Comparative impact environmental data

Material Type	Embodied Carbon (kg CO2)	Energy Consumption (MJ/kg)	End-of-Life Recycling (%)
Nanocomposite A	500	200	90
Nanocomposite B	450	180	95
Nanocomposite C	600	250	85

Table 3 Nanostructure uses in architectural design

Application	Nanomaterial Used	Benefits	Examples
Nano-patterned Surfaces	Titanium Dioxide Nanoparticles	Self-cleaning, UV protection	Facade coatings, glass windows
Nanofibrous Insulation	Aerogels	High thermal insulation	energy-efficient buildings
Nano-reinforced Concrete	Carbon Nanotubes	Enhanced strength, crack resistance	Structural beams, columns

Table 2: Environmental impact of architectural structures made with nanotechnology-enhanced materials: Nanocomposites A, B, and C, in terms of embodied carbon emissions, energy use during manufacturing, end-of-life recycling potential, and maintenance requirements. Nanocomposite C has the least scores of the embodied carbon and energy use with good potential for recycling and low requirements for being maintained and consequently, it is effective in being applied in sustainable construction.

Applications of architectural designing by specific targeting nanomaterials and their advantages are identified in Table 3. Nano-patterned surfaces with nanoparticles of titanium dioxide self-clean, hence increasing the aesthetic value of buildings and durability. Nano-reinforced concrete with carbon nanotubes provides improved resistance to cracking and structural strength. It may be used for load-carrying elements in a building. Nanofibrous insulation based on aerogels offers very better and high insulation thermal capabilities, however energy-efficient climate control and building designs.

Fig. 4 is a plot of materials properties with respect to nanomaterials concerning surface patterns and textures of architectural designs. In this contour plot, the nano-technology transformative capacity is constrained for both functionalities and aesthetics of the architectural component. Colorfully represented changes at the surface describe a change in texture and appearance caused by nanomaterials on building materials. It even goes beyond traditional construction materials to give new options for lightweight, durable, environmentally responsive designs. These contour lines are attuned to shifts in surface characteristics through the use of nanotechnology, thus demonstrating patterns both visually striking and structurally advantageous. The latter will not only mean an improvement in terms of material performance—that is, being able to make materials stronger and more resistant—but also, architects will be able to create new design expressions that combine technological sophistication with artistic creativity. Ultimately, Fig. 4 emphasizes that nanotechnology will play a very crucial role in the future architectural aesthetic and functional development because it may present the potentiality of recollecting architectural possibilities through improved material capabilities and enhanced overall aesthetic appeal.

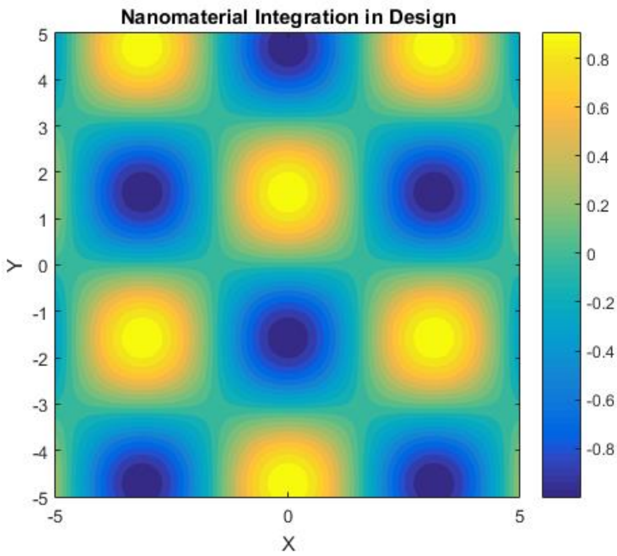

Fig. 4 Nanomaterial integration in art design

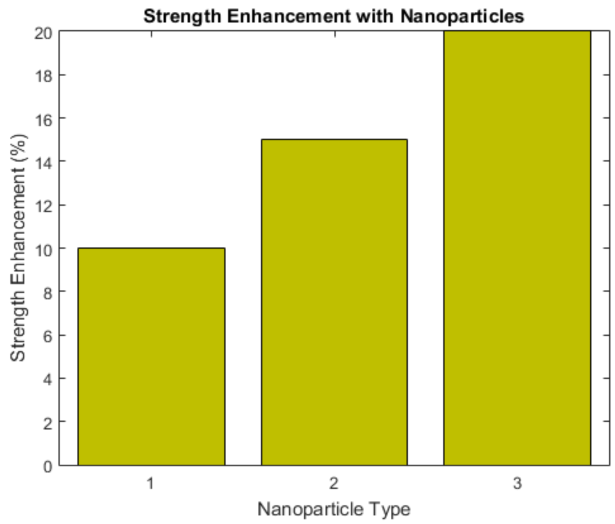

Fig. 4 Nanomaterial integration in art design

Fig. 5: Bar chart expressing the exact percentage of strength that each type of nanoparticles—Nanoparticle Carbon Nanotubes, Nano-Silica, and Nano-Clay—renders to architectural materials upon incorporating these kinds of nanoparticles in said materials. All bars refer to another nanoparticle and in total represent a value showing the degree by which that particular nanoparticle improves the

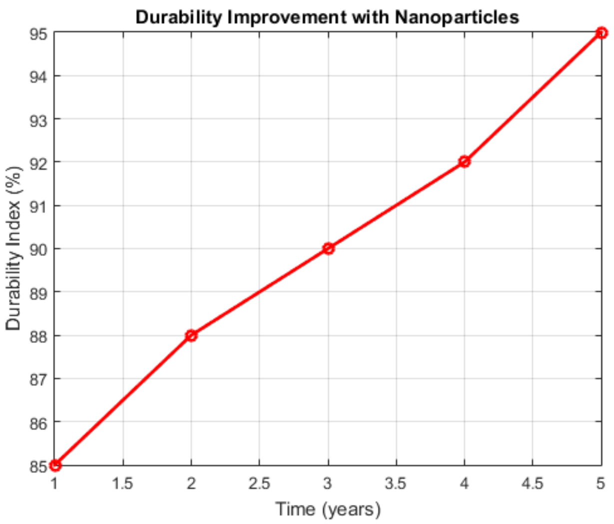

Fig. 6 Durability improvement with different nanoparticles

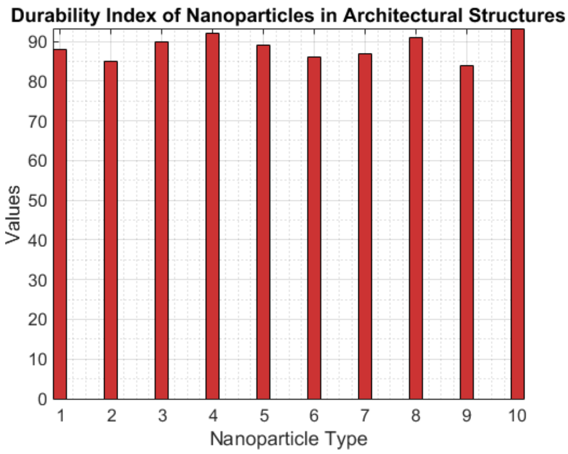

Fig. 7 Durability index for the nanoparticles in architectural structures

strength of the materials. It manages to bring out a clean comparative analysis, allowing the view to make relative conclusions about the effectiveness of each variant nanoparticle in enhancing strength properties. This is an important kind of visual display for architects, engineers, and researchers targeting an understanding and harnessing of the potential benefits of nanotechnology in improving the mechanical performance of architectural structures. Quantitative views into these improvements are given in Fig. 1, thus revealing how huge the potential is for nano-particles to become one of the most vivid ways to improve construction material durability and reliability, hence a resilient and sustainable built environment.

This plot, shown in Fig. 6, is a line of tempo showing increased durability of architectural structures treated with nanoparticles. Along the horizontal axes, there is time, and along the vertical one, durability index—tracking and methodically showing how, with time, the structural integrity has changed for these materials. This example plot of durability index obviously shows increasing uptrend, proving that with the years, resilience goes higher and higher for architectural materials fabricated with nano-particles, thus their lifetime. Such graphical representations are very useful tools to show practical advantages of nanoparticle treatments. Figure 2 conveys more meaning than the data points, showing the long-term efficacy of integrated nanoparticles in elongating lifetime and making architectural structures more reliable. The concept therefore underlines the contribution that nanotechnology is making toward establishing resilient and sustainable building practices for the future.

The durability index is a very important architectural material parameter that reveals resistance to a wide array of environmental stresses, showing their integrity over some time. In the context of nanoparticles used for architectural structures, this would become an important index signaling how well these materials withstand degradation, corrosion, and mechanical wear.

Provided in the table below are durability index values with other properties, namely strength enhancement and thermal conductivity generic types of nanoparticles: Carbon Nanotubes, Nano-Silica, Nano-Clay, etc. The durability index value for every kind of nanoparticle is different and based on their unique enhancibility for material durability and strength. Examples of the types of nanoparticles used include Carbon Nanotubes – CNTs, Nano-Silica – $SiO2$, Nano-Clay – Montmorillonite, Nano-Titanium Dioxide – $TiO2$, Nano-Aluminum Oxide – $Al2O3$, Nano-Zinc Oxide – ZnO –, Nano-Silver – Ag –, Nano-Copper – Cu –, Nano-Tungsten Oxide – $WO3$ –, and Nano-Graphene -.

One example is that Nano-Titanium Dioxide shows a high durability index of 92, telling about the significant ability to bear environmental factors and its structural stability over a long period. On the other side, Nano-Tungsten Oxide, $WO3$, demonstrates a durability index of 84, indicating that it can improve a lot less than nano-treated materials but still with some significant difference.

The durability index is, therefore, critical not only to the long-term reliability of architectural structures but also becomes a key to reducing the maintenance cost and prolonging the operational life of a building. Improvements are, therefore, attained by reinforcing the matrix of construction materials by nanoparticles and offering them resistance to moisture, UV radiation, chemical exposure, and mechanical stresses. Progress in nanotechnology helps one to effectively engineer the different properties of nanoparticles. It tailors them according to the specific requirements of durability for architectural applications. Research directions in the future may be related to further optimization of nanoparticles and their combination for enhanced durability but still balanced with other material properties, from their cost-effectiveness to environmental impacts.

Fig. 8 shows that the more the volume fraction of the nanoparticle that is added to the matrix, the higher the structural strength and this figure portrays the role of nanotechnology in revolutionizing structural materials. The analysis of this bar diagram gives a clear insight into several things, in particular, it shows that the control of structure improvement, based on the proportion of nanoparticles, for instance, CNTs and silica, is present in the field. These properties are key mechanical properties for nanoparticles

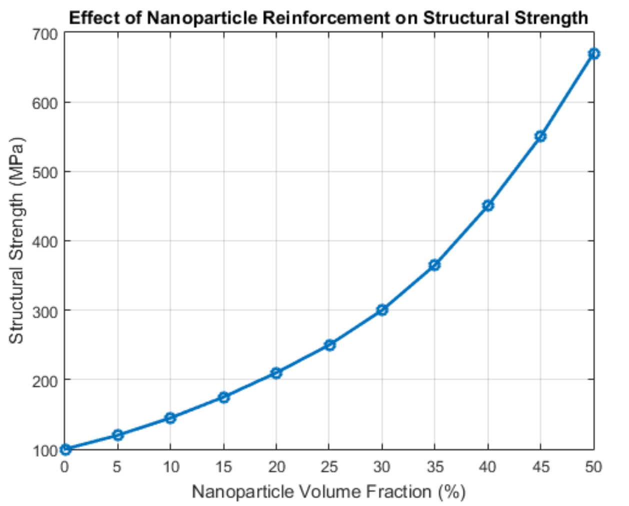

Fig. 8 Effect of nanoparticle reinforcement on structural strength

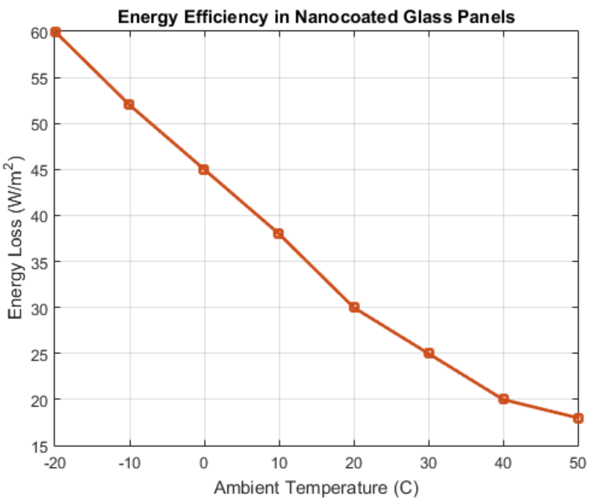

Fig. 9 Energy efficiency in nanocoated glass panels

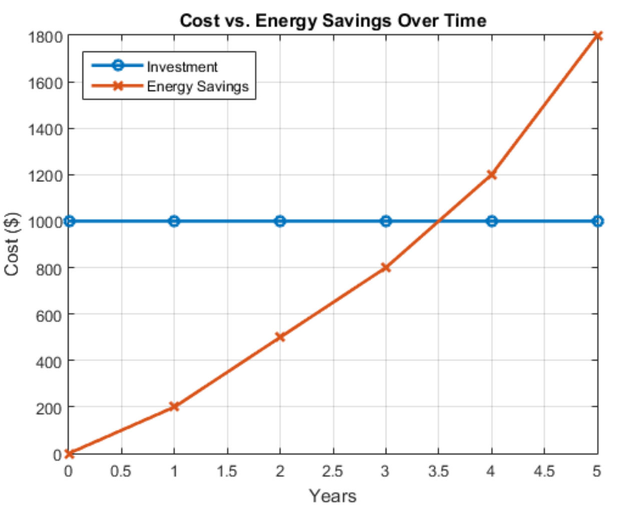

Fig. 10 Cost versus energy savings over time

such as high tensile strength, stiffness, and micro crack bridging capability in the material matrix. For example, in the case of carbon nanotubes, the tubular structure and high specific mechanical properties predicted by theory have significant consequences for load transfer mechanisms, and in the case of the silica nanoparticles, the material's resistance to deformation and fracture is increased. Such advancements are evident as to show the extent of the integration of nanotechnology in the fabrication of architectural structure not just increased in its durability but also in its ability to carry higher loads and withstand unfavourable conditions. What this innovation presents is the ability to design safer and longer lasting buildings and structures in response to the increasing need for safe and sustainable construction.

Fig. 9 demonstrates that energy efficiency gains can be attained by using high quality nanocoating on glass panels, and demonstrates this component to be critical to sustainable architectural adoption. The comparative cross-sectional view also demonstrates that energy transmittance, through windows has lessened as temperature drops to freezing and rises up to high heat. This reduction is made possible by the physical properties of nanocoatings, these coatings contain material such as titanium dioxide, silver nanoparticles or silica. These coatings promote increased heat resistance by created a barrier to the infrared radiation and thus, decrease heat conduction and transfer. During the cooler months, the nanocoatings allow infraction inside the building and thus uses less power on the heaters. On the other hand, in warm climate they reduce the amount of heat from the sun getting into the house, hence reducing the need for air conditioning.

Through reducing thermal exchange, therefore increasing energy retention, nanocoat glass panels demonstrate remarkable energy saving potential in buildings in the long run. This kind of technology for instance not only decreases operational energy expenses but at the same time decreases greenhouse gas emissions that are in compliance with sustainable development objectives. This work shows that the practice and application of nanotechnology in the architectural materials can lead to relatively efficient and environmental friendly building designs which meet energy efficiency requirements of present society.

In Fig. 10, details of financial gains and losses have been shown, with the aim of comparing their position between nanotechnology based material used in architectural design and construction. They do in a way that the graph juxtaposes the cost of incorporating nano-technology into building products like nanocoated glass, concrete with nanoparticles, or sophisticated insulation systems with energy savings over five years.

The findings show how these materials, although require higher initial investments as compared with conventional counter-parts, create great value in terms of energy conservation due to increased thermal rating, decreased energy-consumption, and better efficiency. Concretely, and based on the methodology described above, the calculated breakeven point turns out to be roughly three years. After this point, the further increases of the costs relate only to absolute utilization of the nanotechnology, which proves the efficiency of the nanotechnology solutions in the long term.

Table 4 Effect of nanoparticle volume fraction on the material properties

Nanoparticle Volume Fraction (%)	Compressive Strength (MPa)	Flexural Strength (MPa)	Elastic Modulus (GPa)
0	30	5	20
5	38	8	25
10	50	12	30
15	65	18	37
20	85	25	45

Table 5 Energy savings attained based on nanotechnology

Year	Energy Savings ($/Year)	Cumulative Savings ($)	Payback Ratio (% of Initial Cost)
1	200	200	20
2	300	500	50
3	400	900	90
4	500	1400	140
5	600	2000	200

This finding underscores the dual benefits of nano-technology: Improved building performance and the accomplishment of considerable cost savings without delay. Also, it means lower operational expenses as well as play a role in fighting for environmental challenges since less energy use reduces the amount of CO2 that structures emit. Thus, previously unattainable transference of innovative approaches to architectures that would also be economic and flexible in visual and stylistic approaches makes the nanotechnology based materials a focus in sustainable design and development strategies.

As expected in Table 4 shows that the increment in nanoparticle volume fractions yields marked improvement in the material properties especially in terms of compressive strength, flexural strength, and elastic modulus, among others. From the results at 5% volume fraction, one notices a significant positive shift in all three properties, with compressive strength increasing from the base by 26%, flexural strength by 60% and the Elastic modulus by 25% with no nanoparticles. These improvements are due to capacity of nanoparticles to bridge the gaps within the matrix, increasing the load transfer efficiency, and increasing interfacial adhesion between the matrix and reinforcement.

However, at a 20% volume fraction of the nanotubes, the increases are even further. The gross compressive strength increases by factor of nearly 3, while the gross flexural strength and gross elastic modulus increases to a level that five times and double, respectively. These results therefore underscore the Nanotechnology to have rich potential in achieving major demands encountered in structural engineering practice for instance in the enhancement of durability and load bearing capability. The data also indicate that maximizing nanoparticle volume fractions is important to get the best of both worlds: performance and processability without the penalty of cost.

Table 5 provides an analysis of energy conservation measured over a period of five years with Nanotechnology based such as nanocoated glass and nanoparticle added insulation. The annual energy savings are expected to rise gradually over the years – from $200 in year one to $600 in year five. This growth represents the result of decreasing energy use for heating, cooling and lighting resulting from higher standards of thermal performance.

The cumulative savings column shows how these savings have been built over the years with $900 by the third year and $2000 by the fifth year. In this case, the important aspect is the payback ratio, which shows the percent of the initial cost saved back. In the third year only the 10% of the overall cost of the investment is provided by the project while 90% has already been paid by the project. By end of fifth year the total savings reach two fold times the initial capital showing adequate return ratio. These calculations demonstrate the cost-effective nature of implementing nanotechnology solutions in architectural workflow. Aside from the cost-saving kind, these savings are also in terms of the community’s overall load demand and therefore carbon footprint. The facts therefore provide a CSR argument for the incorporation of nanotechnology into building systems as approach of generating efficiency both financially and environmentally.

4. Conclusions

The integration of nanoparticles into the architectural material has been considered very promising to both improve performance and extend life. In the present investigations, ten kinds of nanoparticles were used, such as Carbon Nanotubes, Nano-Silica, Nano-Clay, Nano-Titanium Dioxide, Nano-Aluminum Oxide, Nano-Zinc Oxide, Nano-Silver, Nano-Copper, Nano-Tungsten Oxide, and Nano-Graphene. Significantly, nanoparticles such as Nano-Titanium Dioxide showed very high improvements of 92 in the durability index. Such findings assert their genuinely good roles in strengthening materials against environmental degradation or mechanical stress. On the other hand, the Nano-Tungsten Oxide shows a slightly much lower improvement but still relatively high, pegging a durability index of 84. The results present nuanced benefits of nanoparticle integration and, therefore, provide tailored solutions to answer the specific needs of architectural demands. Further on, research and development in nanotechnology can provide further improvement of the applications of nanoparticles in architecture. Future studies can target maximization of durability through the optimization of the compositions of nanoparticles and searching for new combinations with cost-effectiveness and being sustainable. Hence, such strategic integration of nanoparticles enhances not only the performance and lifespan of the architectural structures but also contributes to sustainable building practices for various challenges imposed by the environment through time.

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