Chapter 9
Application of Nanoparticles in Construction Industries and Their Toxicity

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Abstract Global development is reflected in the growth of the construction field. To improve the construction related activity and impart the beneficial essence of current technology, nanoparticles are used by the industries at different stages. The size dependent properties of nanoparticles in the construction industry is considered for enhancing material strength, crack recovery, self-cleaning applications, antimicrobial coating, energy conservation and restoration of cultural heritage. Nanoparticles used in the construction industries reach the ecosystem through multiple channels and cause environmental implications such as adverse effects on environmentally relevant microbial species, algae, plants, and entry into the food chain. The exposure to nanoparticles by human beings also causes various health implications such as DNA damage, inflammation and cell death. Therefore, it has become crucial to determine toxicity and assessment of risk during the use of nanoparticles. Their toxicity depends on chemical and physical attributes. Uniform global regulatory policy needs to be framed to assess the toxicity, risk and approval of nanoparticles in the construction industries.

Keywords Additive · Antimicrobial · Health · Nanocoating · Nanoparticle · Thermochromic · Toxicity

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9.1 Introduction

Infrastructure development has gained momentum globally in recent years. At the same time attractive features are incorporated by the construction industries at different stages to enhance the benefits and fulfill the requirements of the end users with the essence of nanotechnology. Richard Feynman introduced the concept of nanotechnology in 1959 while delivering the talk "There's Plenty of Room at the Bottom" at American Physical Society meeting held at California Institute of Technology. Norio Taniguchi coined the word nanotechnology in 1974. The word "nano" is derived from Greek word dwarf (small). The study of objects and phenomena in the range of 1–100 nm is termed as nanoscience. The creation of materials, devices and systems through the arrangement of matter on nano scale is defined as nanotechnology. The nanomaterials can be synthesized using top down and bottom up approaches. Physical, chemical, biological and mechanical methods are widely used for the synthesis of nanoparticles. Most of the synthesized nanomaterials exhibit different properties and effects in comparison to the similar material in a macroscale. The size dependent properties exhibited by nanoparticles in the construction industry are explored for enhancing material strength, crack recovery, acid resistance, self-cleaning applications, antimicrobial coating, fire resistant paints, energy conservation and restoration of cultural heritage. Nanoparticles used in the construction industries reach the ecosystem through multiple channels and cause environmental implications such as adverse effects on environmentally relevant microbial species, algae, plants, and entry into the food chain. The exposure to nanoparticles by human beings also causes various health implications such as DNA damage, inflammation and cell death. Therefore, it has become crucial to determine toxicity and assessment of risk during the use of nanoparticles. Their toxicity depends on chemical and physical attributes such as morphology, composition, uniformity, size, crystallinity, magnetism and surface functionalization. Uniform global regulatory policy needs to be framed to assess the toxicity, risk and approval of nanoparticles.

9.2 Size Dependent Properties

There is an enormous scale difference in the universe. Different forces dominate at different scales and a suitable model explains the phenomena. Nanoscale materials differ from macroscale materials due to the following reasons:

(a) Gravitation force becomes negligible and electromagnetic forces dominate.
(b) Quantum mechanics model is used to describe motion and energy instead of the classical mechanics model.
(c) Greater surface area to volume ratios.
(d) Random molecular motion becomes more important.

The gravity becomes negligible due to the mass of the object at nanoscale. Since the gravitational force is a function of mass and distance, it is weak between nanoscale particles. However, electromagnetic force being a function of charge and distance is not affected by mass, so it can be very strong even when we have nanoscale particles.

The response of material under certain conditions is known as "property". Optical (transparency, color), Chemical (reaction rates, reactivity), Physical (melting point, hardness), Electrical (conductivity), properties are exhibited by nanoscale material compared to its macroscale.

9.3 Nanoparticles in Construction Industry and Application

Nanoparticles exhibit different properties and its usage depends on the specific application. The benefits and applications of various nanoparticles in the construction field are listed in Table 9.1.

9.3.1 Nanoparticles

Widely used nanoparticles in the field of construction are discussed in this section.

9.3.1.1 Silicon Dioxide (SiO_2)

Nano SiO_2 powder is amorphous in nature and appears in white color. Due to the reduced particle size, nano-SiO_2 has many advantages such as greater surface area, enhanced surface adsorption, surface energy, purity and good dispersion. Presence of silicon dioxide in the mortar or cement improves the bonding between aggregates and matrix, reduces porosity, increases the density, particle packing, enhances compressive and flexural strength, facilitates the hydration reaction of concrete and reduces the setting time.

9.3.1.2 Carbon Nanotube

Carbon nanotubes (CNT) are made up of carbon atoms arranged hexagonally. Carbon nanotubes are categorized as single-walled and multi-walled carbon nanotubes. In the field of civil engineering, incorporating CNTs along with cement matrices is exhibiting potential for enhanced mechanical properties and durability. Blending CNT in the cement or mortar improves the tensile strength, flexural strength and compressive strength. CNTs can also have advantages in preventing the microcrack

Table 9.1 Benefits of nanoparticles used in the construction industry

Nanoparticle	Benefit	Application	References
Silicon dioxide	Stability	Additive	Sanchez and Sobolev (2010)
	Resistance to water penetration		
	Protection from fire		
	Self-cleaning		
	Enhanced mechanical properties		
	Frost resistance		
	Refined porosity and microstructure		
	Improved corrosion resistance		
Carbon nanotube	Mechanical strength	Additives	Singh et al. (2017)
	Antibacterial activity		
	Self-cleaning		
	Improved corrosion resistance		
Titanium dioxide	Degradation of air pollutant	Photocatalyst	Colangiuli et al. (2015)
	High compressive and flexural strength	Antibacterial coating	
	Suppress the growth of microorganism	Hydrophobic coatings	
	Prevention of water penetration		
Zirconium dioxide	Tensile strength	Building matrixes	Boulos et al. (2019)
	Suppress the growth of microorganism	Antibacterial coating	
Fe_2O_3	Compressive and flexural strength	Additives	Sanchez and Sobolev (2010)
Vanadium dioxide	Regulate the indoor temperature	Thermochromic smart window	Panagopoulou et al. (2016)
Copper nanoparticle	Corrosion resistance	Additives	Mohajerani et al. (2019)
	Weld ability		
CdSe Quantum Dots	Utilization of solar energy	Photovoltaics	Liu et al. (2020)
Aluminium oxide	Enhanced mechanical properties	Additive	Nazari and Riahi (2011); Behfarnia and Salemi 2013
	Reduction in water absorption		

(continued)

Table 9.1 (continued)

Nanoparticle	Benefit	Application	References
	Refined porosity and microstructure		
	Escalated hydration		
	Frost resistance		
Silver nanoparticles	Antibacterial activity	Additive	Le et al. (2011)
Magnesium oxide	Antibacterial activity	Paint, coating	Huang et al. (2005)
Zinc oxide	Antibacterial activity	Paint, coating	Hochmannova and Vytrasova (2010)

propagation due to the improvement of cementitious materials. It has the chemical resistance property, hence can be used for the constructions prone to chemical exposure. CNT exhibits fire retardant property (Wang et al. 2017).

9.3.1.3 Graphene

Graphene is made up of carbon atoms arranged in the form of sheets. Graphene offers greater tensile strength, better electrical conductivity, anticorrosion and optical properties, hence used for different applications in the construction industry. Flexural strength of the cement can be enhanced by blending graphene. Currently graphene is used as an anti-corrosion coating to protect the steel and photovoltaic panel from the surrounding environment, light emitting diode and touch screen applications inside the building.

9.3.2 Applications

Current section is focused on the potential application of nanoparticles in the construction industry.

9.3.2.1 Additive

Additives are the synthetic or natural material mixed with binding agent, mortars and concrete to achieve desired property in the finished product. Silicon dioxide enhances the stability and prevents the percolation of water. Carbon nanotubes have reported to be enhancing mechanical strength.

9.3.2.2 Self-Healing

The formation of cracks in the concrete structures is a phenomenon that occurs during the service life. Various nanoparticles are adopted to fill the cracks whenever it appears without the external intervention is termed as a self-healing mechanism. Hollow fiber, nanoencapsulation, shape memory materials are explored for self-healing applications. Hollow fibers are filled with healing agents and placed in the concrete structures. During the occurrence of damage to the concrete structure, hollow fibers will break open and release the healing agents to instantly heal the crack (Huseien et al. 2019).

9.3.2.3 Photocatalyst

The concrete mixed with photocatalyst (Titanium dioxide, zinc oxide) will degrade the air pollutants, bacteria, algae and mold using electromagnetic radiation. The photocatalytic reaction takes place in the presence of a light source, when the energy is greater than the band gap of the photocatalyst. The concept is also developed in photocatalytic paint (Dikkar et al. 2020).

9.3.2.4 Antimicrobial

Microorganisms harbouring on the concrete structures such as bacteria, fungi and algae proliferate, propagate and cause various problems. They are responsible for reactions like corrosion, affecting aesthetic appearance, degrading mechanical properties, destroying the internal structure of concrete and reducing durability of concrete. In order to overcome these problems, concrete is blended with nanoparticles exhibiting antimicrobial properties. The nanoparticles of Fe_3O_4, Al_2O_3, CuO, ZnO, TiO_2, $CaCO_3$, and Cu_2O were reported to be effective against microorganisms. Antimicrobial paints and coatings are also available commercially.

9.3.2.5 Nano Paint

As the construction industry is progressing, synergistically the paint industry is growing in terms of the fascinating properties of nanoparticles. To prevent the growth of bacteria, fungus and algae on the building, nanotechnology based paint is gaining importance. The interior and exterior paints are prone to get deteriorated by the microorganism present in the surrounding. Especially during the rainy season due to the moisture condition, different microorganisms grow on the surface. Microorganisms cause damage and distort the appearance of the aesthetics of buildings as well. During the microbial growth, decoloration takes place due to the spore production thus increasing the accumulation of dust. Due to these reasons silver, titanium dioxide, copper in the nanoscale is gaining importance in the paint industry because of its antimicrobial property.

9.3.2.6 Nanocoating

Thin layer of film having nanoscale dimension is used as a protective coating on the construction material. Steel, limestone, concrete, marble and glass are exposed to the environment and prone to undergo corrosion, expansion and growth of microorganisms. The nano coatings are applied to these materials to achieve heat resistance, friction reduction, anti-corrosion and antimicrobial properties. Various coatings are also applied on the window, doors, walls and external surfaces or components to obtain flame-retardant, hydrophilic, hydrophobic, wear-resistant, anti-graffiti, corrosion resistance, photovoltaic properties and provide protection to the base material. Nanoparticles of aluminium oxide, silicon dioxide, titanium oxide and zirconium oxide are incorporated in the coating to enhance the hardness and mechanical properties of the components used in the building materials.

9.3.2.7 Thermochromic

Thermochromic material changes its color reversibly to the corresponding temperature. Indoor solar radiation can be regulated by changing the optical properties of windows with respect to the surrounding temperature. Vanadium oxide exhibits the thermochromic phenomena. Nano crystals of vanadium dioxide are developed by engineering the morphology at nanoscale to improve the performance. In the similar aspectsThermochromic paints are also developed.

9.3.2.8 Photovoltaics

To adopt a sustainability approach in terms of energy generation, building envelopes such as facades, skylights and roofs are integrated with photovoltaics. Parking canopy, wall mountings, cladding are also integrated with photovoltaic.

9.4 Route of Nanoparticle Exposure

As the amalgamation of nanotechnology is escalated, nanoparticles are exposed to the environment and living system causing adverse effects. Nanoparticles are released into the environment at different stages of activity during the manufacturing process, construction site, demolition, recycling process and enter the living system during the consumer use. The nanoparticles released into the environment undergo physical, biological and chemical transformation because of change in their properties.

9.4.1 Manufacturing Process

Synthesis or the manufacturing process of nanoparticles is the primary route for the exposure. As a safety measure, the manufacturing process of nanoparticles is carried out in the enclosed chambers. Hence the chances of nanoparticles released into the air is less and inhalation of nanoparticles during the manufacturing process is not evident. However, during the post manufacturing process such as cleaning or disposal of waste, probably in an unintentional way some nanoparticles get released into the environment. The possibility of dry powder form of nanoparticle releasing inside the laboratory hoods during the handling also is not ruled out.

9.4.2 Construction Site

Nanoparticles released at the construction site will have prolonged exposure in the surrounding atmosphere. People working in the construction site are prone to inhale the nanoparticles causing health implications. There is a necessity that nanoparticle based products need to be handled with utmost care to prevent its dispersion into the air and water. Preparing the silica nanoparticle with cement can be performed in dry or wet form. While preparing the wet form, silica nanoparticles are mixed in water and then dispersed into cement mixture. The process is effective during large scale production and thus avoids the risk of exposure to nanoparticles. Super plasticizers are recommended for preparing the dry form. The coating of nanoparticles in the form of spray must be avoided, since it elevates the risk of exposure. The spray coating will have a higher concentration of nanoparticles when compared to composites.

9.4.3 Demolition

Buildings constructed with nanoparticles incorporated at different stages pose a threat of dispersing nanoparticles to air, water and the surrounding environment during its demolition in future. Currently there is no technology available to recover the nanoparticles embedded with concrete and composite structures. Though it is unavoidable to prevent dispersion of the nanoparticles to the environment during demolition, the coating can be removed to a certain extent.

9.4.4 Natural Phenomena

Due to the continuous exposures of buildings to the environment, damage of buildings, abrasion, and deterioration slowly leads to the release of nanoparticles into the surrounding environment. Natural calamities such as storms, heavy rainfall, floods also cause damage to structures and lead to the leaching of nanoparticles into the water bodies and soil. The accidental fire also releases the nanoparticle into the environment. However, practically it is difficult to analyse the concentration of nanoparticles released into the environment.

9.5 Toxicity

On-going research and development in the field of nanotechnology is exploring different applications in the field of construction industry. At the same time the risk associated with the nano based products on human health and environment is increasing. The study of biological, physical, chemical agents adversely affecting the living system and environment is termed as toxicology. The study of possible adverse effects by the nanomaterials is called nanotoxicology. Toxicity is the degree to which a substance can damage the organism. Nanotechnology has been explored in the various domains due to the impressive benefits. The movement of nanoparticles is much faster than its bulk structure. Due to the dimension of nanoparticles it offers higher surface area, causes reactivity and can diffuse into the cells. Hence it can be more toxic. During the year 1990, the first toxic effect of nanoparticles was reported in which the significant pulmonary inflammation using TiO_2 and Al_2O_3 nanoparticles was reported in comparison with microparticles instilled in rats. Thus focus is shifted to assess the toxicity of the nanomaterials, since more nanotechnology based products are used by mankind.

9.6 Environmental Implications

The nanoparticles are fatal to the growth of Gram negative bacteria due to the presence of thin peptidoglycan layers. In case of Gram positive bacteria, the presence of a thick peptidoglycan layer provides resistance to the nanoparticle effect. Even though the antibacterial property is beneficial during the application point of few, with respect to the environmental perspective it is having a negative impact. In the environment, bacteria has the major role to play in decomposition of organic matter, terrestrial and aquatic food chains, hence negative impact on environmentally relevant bacteria affect the trophic levels. The plants, phytoplanktons exhibit reduced growth rate in presence of higher concentration of nanoparticles by reducing the mitotic index. Mitotic index is the measure of rate of cell division. Copper oxide nanoparticles are reported to induce DNA damage of the plant and reduce the chlorophyll content. Nanoparticles have also been reported to inhibit the seed germination process and root elongation.

9.7 Health Implications

The nanoparticles diffuse into the air much faster than its macro scale particles. The reason is due to the smaller size, shape and greater surface area. Nanoparticles thus present in the air enter into the human body through the inhalation process. Nanoparticles do not have any barrier in the nose to prevent its entry into the human body. They have the ability to cross the cellular barriers and reach the vital organs such as the lung, kidney and liver. Health implications arise due to the damage caused to the mitochondria, DNA by nanoparticles eventually leading to cell death. Nanoparticles can also pass through the blood brain barrier.

The mechanism involved with toxicity of nanomaterials is reported to be through oxidative stress which damages proteins, carbohydrates, DNA, lipids and potential to change the properties of cell membrane disrupting vital cellular functions. The oxidative stress triggered by nanoparticles depends on particle uptake, presence of transition metals and mutagens, solubility, composition, shape, size and aggregation.

The silicon dioxide nanoparticles are reported to accumulate in the brain, kidney, spleen, liver and heart after the entry into the human body through pulmonary exposure and skin. The nanoparticle causes the generation of reactive oxygen species and brings oxidative stress, further leading to cell death. Significant DNA damage in endothelial cells was reported due to the silicon dioxide nanoparticle.

Titanium dioxide is extensively used in nanoparticles in the construction industry. Titanium dioxide exhibits genotoxic, cytotoxic and oxidative effects causing apoptosis and inflammation (Proquin et al. 2017). Titanium dioxide has been listed as a potential cancer causing agent by the International Agency for Research on Cancer. The exposure limit is recommended to be 0.3 mg/m^3 by the Institute of Occupational Safety and Health. The policy focusing on nanotoxicity has to be made uniform across the world to take necessary preventive steps. Risk assessment and management for the building material incorporated with nanoparticles has to be carried out.

9.8 Conclusion

Nanotechnology based products are promising in the field of construction industry. Various nanoparticles have gained the space in paint, coating, additives due to its fascinating properties such as increased mechanical strength, and anti-corrosion, antibacterial properties. Prevention of release of nanoparticles to the ecosystem has to be monitored and regulated. However the standard operating protocol needs to be developed for the safety of stakeholders. Nanotoxicology studies need to be taken up for all the nano based products to assess the risk and instil confidence among the users.

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