Chapter 8
Nanoparticles in Construction Industry and Their Toxicity

G. Santhosh and G. P. Nayaka

Abstract Nanoparticles (NPs) are ultrafine particles having size between 1 to 100 nm. For a few decades, the researchers have explored wide scientific applications of NPs in medicine, electronics, construction, manufacturing and in insulating materials. The benefits of using NPs in construction materials are huge; the NPs can modify the physical, thermal, antimicrobial, self-cleaning and self-sensing, and self-healing and chemical properties of construction materials. NPs such as titanium dioxide, carbon nanotubes, clay and aluminium dioxide are widely used in construction materials. The NPs used in the construction materials are released to the environment or the workers handling the materials likely to be exposed to the NPs, the exposure can be detrimental to the environment and human health. NPs can enter the human body through skin, via inhalation or ingestion. However, the rate of exposure to NPs can cause serious respiratory, cardiovascular, skin and nerve related diseases. This chapter briefs about the importance of NPs in construction materials/industry together with their adverse effects on environment and human life.

Keywords Antimicrobial · Construction industry · Environment · Mechanical · Nanoparticles · Toxicity

8.1 Introduction

The recent reports on urbanization indicate that over 54% of the world's population live in cities, this number may increase by 12% by 2050 (United nation 2014). The urbanization needs economic and social reforms as a part of development, these reforms may bring huge stress on the environment. This development in the cities

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Fig. 8.1 Huge quantity of building waste dumped in the open environment

may increase the pollutants produced by the large quantity of constructional wastes (Tixier et al. 2011; Agudelo-Castaneda et al. 2017).

The constructional waste generated also includes unused materials due to excess supply or mishandling (Akhtar and Sarmah 2018). However, the construction waste is inert, the major problem is its volume and weight due its large production throughout the globe (Galvez-Martos et al. 2018). The handling of the constructional waste is the major issue worldwide due to the environmental impacts by their constituent products (Akhtar and Sarmah 2018). The large quantity of construction waste dumped in the open environment is shown in Fig. 8.1. The use of nanoparticles and nanofibers in constructional materials is increasing day by day, the toxicity of nanomaterials on environment through construction materials during their manufacturing and recycling is focus of many researchers these days.

The term 'nano' was coined by famous physicist 'Richard Feynman'. The nanomaterials revolution has increased a variety of industrial products including the construction materials (Sanchez et al. 2010). Because nanomaterials have excellent surface activity and can be used in various applications, especially in the construction sectors. The nanomaterials are engineered either through top-down or bottom-up approach (Xing et al. 2016). The top-down approach involves the breakdown of large structures into smaller materials of nano dimensions whilst the bottom-up approach involves the piecing of nano sized molecules into larger structures or until the required size is achieved (Xing et al. 2016). Further, these nanomaterials are prepared by techniques such as chemical and physical method. Few nanoparticles prepared by these methods are listed in the Table 8.1.

The nanoparticles can be used as additives or reinforcing materials to enhance the overall characteristic of concrete, mortar, paints, and in insulating materials (Ribeiro et al. 2013; Farzadnia et al. 2013; Aziz 2016; Yan et al. 2017; Ribeiro et al. 2015). Nanoparticles such as SiO_2, Al_2O_3, TiO_2, Fe_2O_3, $CaCO_3$, CuO, nano-metakaolin and nano-magnesium calcite are used in cement-based materials to improve mechanical, thermal and electrical properties (Rashad 2013; Silvestre et al. 2016; Abo-El-Enein et al. 2014; Abdel-Gawwad et al. 2019; Noorvand et al. 2013; Mohseni et al. 2015). The use of above-mentioned nanoparticles can change the kinetics and hydration

Table 8.1 Nanoparticles prepared by chemical and physical techniques

Method	Technique	Nanoparticles
Chemical	Sol-Gel	Metals, oxides, carbides, nitrides etc.,
	Vapour phase reaction	
	Evaporation or condensation	
	Reaction in liquid medium	
	Reaction in solid medium	
Physical	Laser	Metal oxides, fullerenes, semiconductors etc.,
	Plasma synthesis	
	Electronic irradiation	
	Physical vapour deposition	
	Densification and consolidation	

of the cement. Silica fume, fly ash and nanosilica particles are also widely used in cement and concrete industries. On the other hand, nano-metakaolin, nanosilica and nano-alumina enhance the physical properties of the mortar due to their high pozzolanic and nucleating activities nanoparticles. The lightweight aggregates such as vermiculite and perlite are used as fire protecting mortars; these aggregates are also suitable to protect other constructional materials as well.

The successful use of nanoparticles in the construction materials makes it more likely for the workers to be exposed to the toxic particles released by the construction materials. The toxicity of the nanoparticles depends on a few conditions, such as nanomaterials concentration, frequency and duration of exposure. However, the use of advanced technologies does not always have a positive impact on the environment. It is very much essential for mankind to address these issues to fully understand the limitations of the nanoparticles on the environment and relevant safety concerns.

8.2 Importance of Nanomaterials in Construction

The nanoparticles are wonderful because of their nanoscale size (1–100 nm); the crucial factor of the nanoparticles is the size, the materials properties significantly improve in the presence of nanoparticles. The use of nanoparticles can bring many important parameters and behaviour in the bulk materials, electrostatic forces and quantum effects start to dominate. These properties of nanoparticles bring extraordinary changes in the physico-mechanical and physical–chemical behaviour of constructional materials (Table 8.2). Typical nanostructures like cylindrical, spherical and sheets with high quantum effects and high surface to volume ratio have changed the entire chemistry of constructional materials. The properties such as increased strength, self-sensing, self-cleaning, antimicrobial, or pollution remediation capabilities can be improved with the addition of nanoparticles in the construction materials.

Table 8.2 Nanomaterials used in construction materials

Construction materials	Nanoparticles	Properties enhanced
Concrete	Silica, Titania, CNTs, Iron oxide	Mechanical strength, Hydration, crack prevention, compressive strength, Abrasion-resistant
Asphalt concrete Timber	Aluminium oxide, Zycosoil	Life, Higher compaction
Bricks mortar	Clay nanoparticles	compressive strength, Increased surface roughness
Steel	Copper	Corrosion resistance, fatigue life

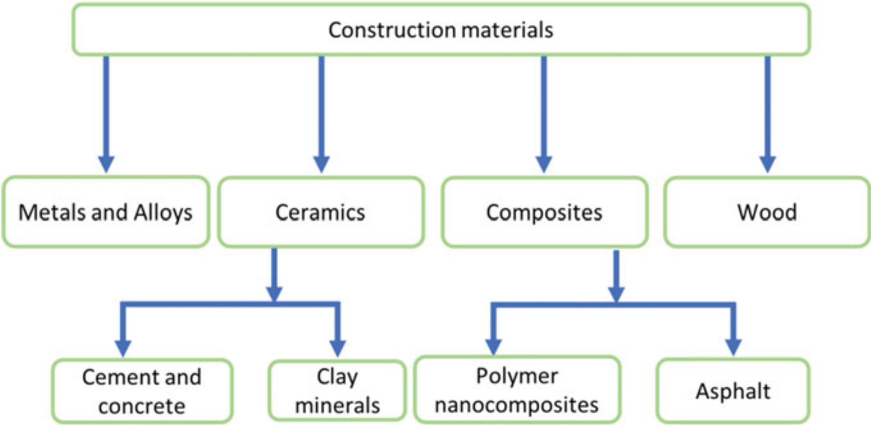

Fig. 8.2 Various materials used in the constructional sectors

The typical construction and building materials used are presented in Fig. 8.2. The construction sector is rapidly growing and there has been a notable change in the industry due to the advancement of nanoscience and technology.

8.3 Nanomaterials in Construction

Nanoparticles can help materials with unique behaviours; the constructional materials can be lighter, stronger with better insulation and acoustic behaviours. The nanoparticle with low density and high strength provides new roots to the market growth for constructional sectors. Nanoparticles have replaced the natural materials by improving the performance of building materials, further, nanoparticles in construction offer better, cheaper, safer and faster approach for the production of building materials. The use of nanoparticles in the raw materials can significantly enhance the product durability and efficiency to newer levels. Nanoscience and technology have greater potential in changing the construction industry into targeted environmental protection.

8.3.1 Concrete and Cement

Concrete and cement are the major construction materials used for decades. These materials are very famous for their performance in buildings. These materials are famous not only because of their high performance; they are famous for their low cost and availability. Further their properties are enhanced by the addition of nanoparticles. The components of cement these days include binders, water and aggregate materials (Nazari et al. 2011). The properties of the concrete can be modified by for particular applications nanoparticles are added (Mohajerani et al. 2019a). It is very much essential to enhance the durability and serviceability of the concrete as it is exposed to different weather conditions. The durability of the concrete can be improved by creating an interface between the concrete components (Salemi et al. 2013). Nanoparticles such as nano-silica, TiO_2 and CNT are used to improve the strength and durability of concrete.

The addition of nano-silica in cement and concrete can significantly reduce the water penetration (Tiwary et al. 2013). Nano-silica, suitable binding materials for cement, can delay the degradation of calcium silicate hydrate (Ca-Si-H), thereby improving the cohesivity between cement and aggregate molecules (Salemi et al. 2013).

CNTs with one-dimensional hollow structure are an emerging filler material in construction sectors. CNTs in concrete can enhance the mechanical property and make concrete impenetrable to salts and water (Konsta-Gdoutos et al. 2010).

Nano-titania (TiO_2) is another nanoparticle which has been widely used in construction materials due to its high surface area. TiO_2 used in concrete can enhance the anticorrosive and photo-catalytic activity, the concrete in the presence of TiO_2 can become self-cleaning and self-disinfecting against the pollutants. TiO_2 in the presence of light breaks the pollutants into water and Co_2 (Khitab 2016). Polycarboxylate ether is a third-generation super plasticizer which is a well-known strength improver that helps in particle dispersion and reduces water content in cement.

8.3.2 Asphalt

Asphalt is the most famous composite material primarily used in road construction. Asphalt can withstand high load for longer duration. Asphalt has very poor response to high and low temperatures, but it becomes vulnerable at high temperatures resulting in melting and cracks can be seen at low temperatures (Rahman et al. 2017). However, this behaviour can be altered by the addition of suitable filler materials/nanomaterials.

Styrene–butadiene–styrene (SBS), polyethylene (PE) and styrene–butadiene–rubber (SBR) are most appreciated modifiers; these can change the elastic and ductile nature of Asphalt to encounter extreme temperature (Zhang et al. 2016). Nano-aluminium oxide (Al_2O_3) is one of the main nanomaterials, with just 5% addition of Al_2O_3 in asphalt cement increases its resistance to high temperatures (Mubaraki et al. 2016). Further, other problems such as stiffness, durability and strength can be altered by adding various nano-modifiers, Zycosoil is an anti-strip agent used to enhance the fatigue life of the concrete or cement (Sarkar et al. 2014).

8.3.3 Bricks

Bricks are the major construction materials for many decades. Bricks consist of clay, sand and few granular materials. These ingredients bind together at a very high temperature to form a brick with good compressive strength (Mohajerani et al. 2016; Mohajerani et al. 2019b). However, these days the addition of nano-clays in the process increases the compressive strength of the brick by 4.8 times (Niroumand et al. 2013). Further to increase the durability of the bricks alko siloxane and silica nanoparticles were added to protect the bricks. The modified bricks showed high resistance to the water uptake with improved durability (Stefanidou et al. 2016).

8.3.4 Mortar

The mortar binder used in the constructional materials has good permeable properties which helps in quick evaporation of moisture from the construction martials. However, water penetration is an important issue that needs to be addressed. The water penetration can cause materials loss hindering the strength of the binder. If the binding material degrades, then the whole material would soon follow. Hence, to use the mortar in water rich areas organic oils or wax are coated.

8.3.5 Steel

Steel is the major and commonly used construction material in all construction works due their durability, high strength to weight ratio and their fire-resistant behaviour. The steel used in huge buildings and bridges face many issues related to strength and corrosion. These issues can be addressed by the use of nanofillers. The copper nanoparticle used as a modifier can enhance the surface roughness of the steel. The anti-corrosion property of the steel can be with just 0.5% of copper nanoparticles solution (Ge et al. 2008).

In addition to the construction materials, various nanoparticles are used in different construction applications and products. Coating nano TiO_2 on walls, and roofs behaves as an anti-fouling agent (Irie et al. 2004; Zhu et al. 2004). Silver nanoparticles in paints can increase antimicrobial property of the (Kumar et al. 2008). CNTs, fullerenes and quantum dots used in cements can enhance the durability and mechanical strength of the cement (Mahendra et al. 2008).

8.4 Environmental Release and Exposure Scenarios

In the name of development, the use and production of nanoparticles has increased, and their release into the environment increases the potential adverse effects on mankind and environment. Exposure analysis is crucial in assessing and preventing the unwanted influence of the nanoparticles on the environment. The risk assessment is very important regardless of nano-toxicity; the poor exposure can prevent the possible health risk. This can be accomplished by proper handling and disposal of nanoparticles in the environment. Further, it is very much essential to analyse the concentration to which the humans are exposed to, it is essential to determine whether nanoparticles retain their structure and reactivity is the big challenge to assess their bioactivity and impact on humans and environment. The manufactured nanoparticles can enter the ecosystem either during manufacturing or when used or when disposed intentionally/unintentionally (Klaine et al. 2008; Wiesner et al. 2006). Despite the awareness of release of nanoparticles, attempts to identify and characterise overriding exposure routes have been quite preliminary. Furthermore, many researchers have studied and evaluated the hazards and impacts of nanoparticles (Griffitt et al. 2007; Lin et al. 2008; Oberdörster et al. 2004; Zhu et al. 2008).

Few studies have shown the environmental implications by nanoparticles fate, transport, transformation, bioaccumulation and bioavailability (Chen et al. 2006a, b; Fortner et al. 2005; Kandlikar et al. 2007; Lee et al. 2008). The studies suggest that the nanoparticles have the ability to affect the environmental and human health (Kirchner et al. 2005; O'Brien et al. 2008), they fail to provide the regulatory guidelines for the safe production, safe disposal of the building nanomaterials. Therefore, understanding the release and reactive behaviours of the nanomaterials represents critical knowledge gaps for the risk assessment (Kartam et al. 2004; Kourmpanis et al. 2008; Poon 2007).

8.5 Toxicity of Nanomaterials

Nanoparticles reinforced construction materials can cause cellular toxicity via multiple mechanisms. The mechanism may include disruption of cell walls, nucleic acid damage, and release of toxic metal ions. Table 8.3 presents the toxic effects of nanoparticles used in building materials.

Table 8.3 Different nanoparticles used in building materials and their toxic effects

Nanoparticle	Effect	Organism	Reference
CNTs	Membrane damage	Bacteria	Ding et al. (2005), Kang et al. (2007), Lam et al. (2006)
Quantum dots	Toxic metal ions can damage DNA	Human cells	Chang et al. (2006), Hoshino et al. (2004), Ryman-Rasmussen et al. (2007), Shiohara et al. (2004)
	Prevents the bacterial growth (Bactericidal)	Bacteria	Kloepfer et al. (2005), Mahendra et al. (2008)
SiO_2	Reactive oxygen species (ROS) are produced and can cause toxicity	Bacteria	Adams et al. (2006)
TiO_2	Growth inhibition, Photosynthesis can be stopped, oxidative damage due to ROS	Bacteria, algae, fish	Blaise et al. (2008), Long et al. (2006), Lyon et al. (2006), Rincon et al. (2004), Wolfrum et al. (2002)

The hazardous effects may range from no damage to sub-lethal effects to mortality. CNTs and TiO_2 nanoparticles are the most widely studied due to their potential hazardous effects. TiO_2 is a prominent photoactive nanoparticle that causes inflammation, cytotoxicity and has the ability to damage DNA of mammalian cells as it can produce ROS (Handy et al. 2008; Karlsson et al. 2008; Oberdorster et al. 1995; Park et al. 2007; Reeves et al. 2008; Sayes et al. 2006; Zhang et al. 1998; Zhu et al. 2008). The major reason for the toxic effect is its morphology, the TiO_2 nanoparticle loose its mobility inside the cells allowing pathogens to generate ROS (Long et al. 2006). CNTs used in the constructional materials can exert pulmonary toxicity (Ding et al., 2005; Jia et al. 2005; Wei et al. 2007). The direct interaction of CNTs with cells can damage the cell walls by creating oxidative stress (Narayan et al. 2005; Kang et al. 2007).Copper based nanoparticles also exhibit strong oxidative stress and have the ability to damage human DNA (Chen et al. 2006a, b; Blaise et al. 2008; Karlsson et al. 2008; Lee et al. 2008). The SiO_2 nanoparticles have categorised as human carcinogens (IARC 1997), the SiO_2 nanoparticles have the ability to induce tumour necrosis (Attik et al. 2008). Ultra-fine nano sized SiO_2 at high concentration can damage water bacteria (Adams et al. 2006). Quantum dots (QDs) are another class of nanoparticles used in various industrial applications. Fluorescent QDs having heavy metals are decorated with organic functionalities to enhance their stability (Yu et al. 2007), the release of heavy metals such as cadmium, lead and zinc can be toxic to bacteria and mammalian cells (Kloepfer et al. 2005; Mahendra et al. 2008; Cha et al. 2007; Derfus et al. 2004; Hardman et al. 2006; Kirchner et al. 2005; Lu et al. 2008; Shiohara et al. 2004). The release of heavy metals can be controlled by surface coating, however, sometimes the surface coatings itself have become toxic to mammalian cells (Hoshino et al. 2004; Lee et al. 2007; Ryman-Rasmussen et al.

2007). On the other hand, the toxicity of QDs can cause oxidative stress, cytotoxicity and nucleic acid damage (Chang et al. 2006; Lin et al. 2008; Lovric et al. 2005).

8.6 Risk Assessment and Analysis

In general, Nanomaterials as we know existed from nature and are used in various applications from ages, however humans are creating a variety of nanoparticles using advanced techniques to meet the current engineering requirements and hence there will be issues regarding their adverse effects on the environment and humans. The nanoparticles are highly active and unstable materials due to their size and high surface to volume ratio makes them suitable materials in various industrial applications. However, the market volumes for the production of nanomaterials have grown tremendously over the last few years.

The use of nanomaterials makes us understand the quantification of exposure and hazard are important in assessing the environmental risk. The critical assessment includes problem identification and problem prioritization based on the impact on the environment (Maynard et al. 2006). These assessments help us address the impacts of one or more nanoparticles. Further, they help us in analysing its worth spending time and money in quantification of risk assessment. This risk assessment process depends on parameters like scientific evidence, general public opinion, advantages and perception of the risk. In other words, industries must have a multidisciplinary approach to process the constructional waste, the waste generated must be reused as input for the new process or to generate new materials and components.

8.7 Critical Knowledge Gaps and Research Needs

Nanoparticles are the most promising and common features in many constructional materials due to their unique and remarkable properties. However, their production and use creates a huge impact on human health and the environment. The adverse effects of nanomaterials used motivating huge research fraternity to concentrate not only on risk assessment, but also on their safe handling and disposal.

Nanoparticles are ultra-fine molecules that have the ability to penetrate into the human cells and to cause many respiratory and skin related issues, but the mode of action of nanoparticles is still a mystery. In particular, the nanoparticles size distribution, chemical stability, bioactivity, and toxicity are not fully understood. Thus, a complete mechanism to understand their structure-reactivity related to immunology and toxicity is necessary. The researchers must expand their research to address the sublethal chronic exposure and their impact on organisms.

The analytical techniques used to quantify the effect on nanoparticles are insufficient in accessing the environmental impacts. Thus, few advanced techniques are necessary to address the metrology of nanoparticles to understand their fate and transformation in different environmental conditions. The improv techniques should be able to monitor the short-term and long-term workers exposure during manufacturing, construction and demolition processes.

Ultimately, the education system must motivate the young minds to research and identify an efficient way to reuse and recycle the constructional materials or constructional wates. The advance research may force the authorities to enforce appropriate guidelines and regulations to mitigate the environmental risks.

8.8 Conclusions

This book chapter presents a brief idea about a few nanomaterials used in construction and building materials. Nanotechnology is so unique in such a way that the use of nanomaterials has created a huge impression in various industrial applications, with the use of nanomaterials new challenges have emerged in terms of biocompatibility, toxicity and their impact on human life. The most widely used nanoparticles in different construction materials such as cement and concrete, asphalt, bricks, mortar and steel are presented. However, nanoscience is still an emerging field with many opportunities and challenges. Each day the use of nanomaterial creates new problems to assess and analyse in the construction industry. Eventually, the effects of nanoparticles on the environment and human health create a huge void in understanding their nature and behaviour. However, the research reveals the negative impact of nanomaterials on environment and human life, stringent action plans and guidelines must be adopted to avoid the environmental risks.

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