Environmental Engineering and Management Journal
November 2019, Vol. 18, No. 11, 2305-2318
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

NANOMATERIALS IN CONSTRUCTION AND THEIR POTENTIAL IMPACTS ON HUMAN HEALTH AND THE ENVIRONMENT

Saeed Kamali[1]*, Sonia Sanajou[2], Mohammad Nima Tazehzadeh[3]

[1]*Civil Engineering Department, Middle East Technical University, 06800, Ankara, Turkey*
[2]*Faculty of Pharmacy, Eastern Mediterranean University, 99628, Famagusta, North Cyprus, Via Mersin 10, Turkey*
[3]*Civil Engineering Department, Eastern Mediterranean University, 99628, Famagusta, North Cyprus, Via Mersin 10, Turkey*

Abstract

Over the last few years, the use of nanomaterials in the construction industry has grown prominently. Nanomaterials can considerably modify the properties of construction materials and even improve their performance. Despite their merits, considerable research has reported that nanomaterials pose a potential risk to human health. For this reason, it is important to fully comprehend the effects of nanomaterials on human health and the environment throughout all phases of their life cycle, including manufacturing, construction use, and recycling, in order to ensure their responsible usage. This research reviews the use of nanomaterials to enhance the properties of conventional construction materials as well as the possible adverse exposure scenarios for humans and the environment. Moreover, the potential risks and negative biological effects of these materials on human health are debated. This study serves to raise awareness of the potential hazards of nanomaterials, especially on human health and the environment.

Key words: construction industry, environment, human health, nanomaterials, toxic effects

Received: October, 2018; Revised final: March, 2019; Accepted: March, 2019; Published in final edited form: November, 2019

1. Introduction

Nanomaterials have been defined as materials with at least one dimension in the range of 1–100 nm (Ju-Nam and Lead, 2008). In October 2011, the European Commission provided the following extended definition: "a natural, incidental or manufactured material containing particles in an unbound state, or as an aggregate, or as an agglomerate; and where, for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range of 1 nm to 100 nm. In specific cases and where warranted by concerns, for the environment, health, safety or competitiveness the number size distribution threshold of 50% may be replaced by a threshold between 1 and 50%" (Díaz-Soler et al., 2016). Today, nanomaterials have become one of the most powerful innovation engines (Aguar-Fernandez and Hullmann, 2007; Zweck et al., 2008), enhancing a variety of services and products with widespread applications across multiple scientific fields (Sharma et al., 2015), such as biology (Sarikaya et al., 2003), physics (Pearce, 2012), chemistry (Whitesides, 2005), materials science (Gao et al., 2018; Shimomura and Sawadaishi, 2001), cement-based materials for construction and waste immobilization (Aguiar et al., 2017; Saleh et al., 2018; Saleh et al., 2019), pharmaceutical (Putheti et al., 2008), cosmetics (Singh and Nanda, 2012), and engineering (Arico et al., 2005; Dai, 2006; Schmid and Riediker, 2008). However, the possible adverse health and environmental effects of nanomaterials are still ambiguous (Yokel and MacPhail, 2011) because of their novel properties (Beaudrie et al., 2015). However, an accidental or incidental release of nanomaterials can pose certain risks to human health

---

* Author to whom all correspondence should be addressed: e-mail: saeedkamali2002@gmail.com, saeed.kamali@metu.edu.tr; Phone: +90 5396973159

and the environment, such as fibrosis, cytotoxicity, and carcinogenicity (Bergamaschi et al., 2015; Hallock et al., 2009; Schimpel et al., 2017; Subramanian et al., 2016; Van Broekhuizen et al., 2011; Yokel and MacPhail, 2011).

Current state-of-the-art research into the potential hazards and occupational safety of nanomaterials is still based on a limited but growing toxicological database (Kuempel et al., 2012, Jones et al., 2017); hence, a research-to-practice approach is currently used to evaluate and minimize the potential hazards. Due to uncertainties such as insufficient quantitative clinical data and inadequate labeling of products containing nanomaterials, conventional risk assessment frameworks have failed to estimate the risk of exposure to nanomaterials (Justo-Hanani and Dayan, 2015) leading to ambiguous qualitative risk estimates (Bergamaschi et al., 2015). The lack of a standardized framework poses a significant challenge to evaluating and interpreting the continuously accumulating research finding, which hinders the delivery of practical guidance and action and could result in the failure to support timely regulatory decision (Bergamaschi et al., 2015; Kuempel et al., 2012; Lee et al., 2010). For example, workers will employ different levels of protection depending on the health effects data available for a specific substance and the extent to which exposure controls are implemented (Kuempel et al., 2012).

Nanomaterials have been identified as a Key Enabling Technology. It has been predicted that half of all construction products will contain nanomaterials by the year 2025 (Jones et al., 2017). Nonetheless, several historical examples have demonstrated the unforeseen negative impacts of initially promising technologies on the environment or human health. One such example is that of thalidomide, which was used for the treatment of nausea (morning sickness) in pregnant women, but was later found to be the cause of birth defects (malformed limbs) in thousands of children (Kim and Scialli, 2011). Furthermore, nanomaterials are regarded as reactive materials because of their high surface area to volume ratio. Consequently, a number of biological and chemical transformations may occur within these materials at a construction site, such as redox reactions, bioreaction, dissolution, and aggregation (Al-Bayati and Al-Zubaidi, 2018). Therefore, it is vital to identify the potential adverse impacts of nanomaterials in the construction industry to biological systems such as human health and the environment then perform risk assessments to mitigate the identified potential impacts.

This study aims to raise awareness of the potential risks of nanomaterials on human health and the environment. A state-of-the-art overview of the applications of nanomaterials in the construction industry, as well as the potential risks and adverse biological effects of nanomaterials on human health and the environment, is presented. This paper is divided into four main sections. In the first section, the most common nanomaterials used in the construction industry are described according to their application. The potential environmental impacts of nanomaterials, as well as possible exposure scenarios, are discussed in the second section. Risk management of the potential exposure to nanomaterials is discussed in the third section. Finally, the potential risks of nanomaterials to human health and their adverse biological effects are debated in the last section.

2. Application of nanomaterials in the construction industry

The construction industry, as a high-volume consumer of materials, has significant potential for nanomaterial applications (Ge and Gao, 2008; Hanus and Harris, 2013). Over the last couple of decades, numerous nanomaterial applications have been developed for the construction industry in order to enhance material performance such as improved durability (Pacheco-Torgal and Jalali, 2011), strength (Chuah et al., 2014), energy efficiency (Arico et al., 2005), and ease of maintenance (Chen and Poon, 2009). The Centre for Construction Research and Training (CPWR) identified approximately 600 construction products in the USA that might contain nanomaterials (http://nano.elcosh.org).

These recent applications of nanomaterials have been developed for cement and concrete (Jayapalan et al., 2009; Saleh et al., 2018; Saleh et al., 2019), steel (Wang and Li, 2003), insulation materials (Baetens et al., 2011), paints (Hochmannova and Vytrasova, 2010), coatings (Makhlouf and Tiginyanu, 2011), and glass (Lin et al., 2013a; Yaghoubi et al., 2010). Another application known as Smog-Busting pavement has also been developed (Shen et al., 2012) but is not yet widely used (Bartos, 2014).

Nanomaterials are used to increase concrete elasticity and mechanical integrity, decrease the weight of concrete, reduce porosity, enhance material fire resistance, and decrease building energy consumption by enhancing the performance of insulation materials. However, inadequate labeling of construction products makes it difficult to identify the exact nanomaterial contained in each product. In addition, it is a widespread marketing strategy to use the term of "nano" in the product name without any conspicuous properties to suggest nano-enablement (Jones et al., 2017). For these reasons, it is not easy to obtain detailed information about the products; this lack of published data has been corroborated by a number of researchers (Jones et al., 2017; West et al., 2016).

Nanoparticles can be applied in construction materials to improve cementitious material properties, decrease thermal transfer rate, and reduce coating maintenance costs. A number of these applications are shown in Fig. 1. According to previous research, the most common nanoparticles used in the construction industry are detailed below and summarized in Table 1.

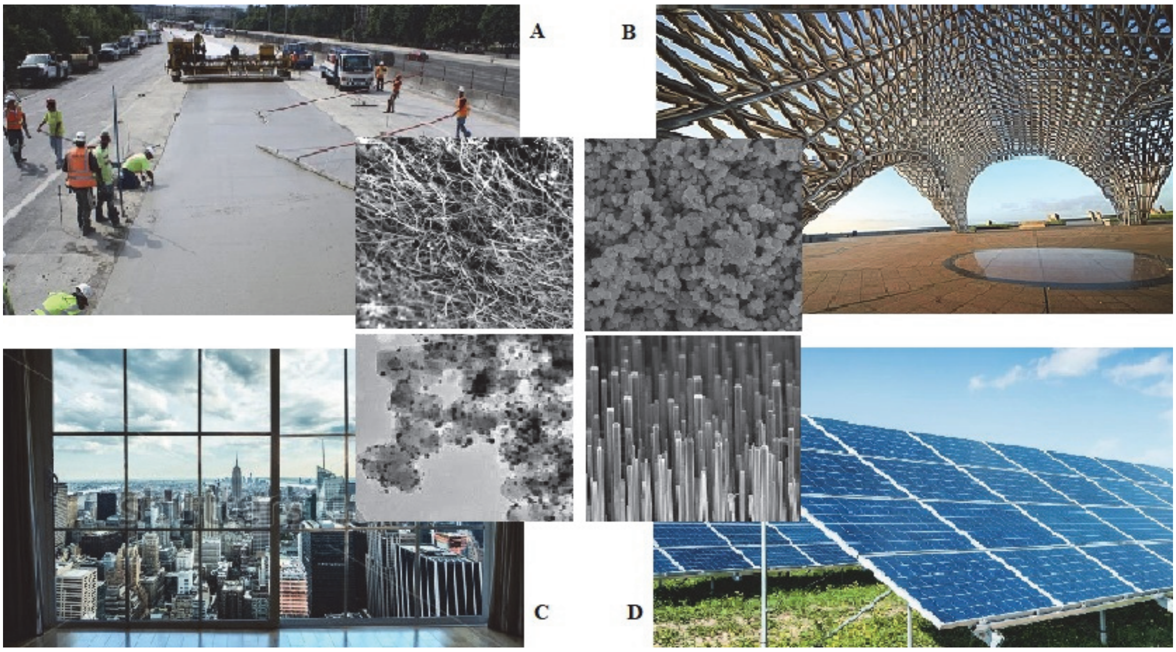

Fig. 1. Nanomaterial applications in the construction industry. (A) Concrete pavement with carbon nanofibers, (B) Steel structure with copper nanoparticles, (C) Window coated with TiO_2 nanoparticles, and (D) Photovoltaic solar panel with arrays of silicon/TiO_2 nanowires (Lee et al., 2010).

Table 1. Commonly used nanomaterials in the construction industry and their applications

Construction material	*Nanoparticle*	*Expected benefit*	*References*
Concrete	SiO_2	Corrosion reduction; improved strength	(Van Broekhuizen et al., 2011; Saleh et al., 2018)
	TiO_2	Fast hydration; self-cleaning; increased durability	(Raki et al., 2010; Van Broekhuizen et al., 2011; Saleh et al., 2019)
	Fe_2O_3	Abrasion-resistance; improved compressive strength	(Raki et al. 2010)
	CNTs	Crack prevention; increased durability	(Ge and Gao, 2008; Raki et al., 2010)
Ceramic	SiO_2	Coolant; light transmission; fire resistance	(Lee et al., 2010)
	CNTs	Improved thermal and mechanical properties	(Luo et al., 2004)
Glass	SiO_2	Antireflection glass; fire protection; self-cleaning	(Mann, 2006; Rana et al., 2009; Van Broekhuizen et al., 2011)
	TiO_2	Super-hydrophilicity; anti-fogging; fouling resistance;	(Irie et al., 2004; Kontos et al., 2007; Van Broekhuizen et al., 2011; Zhu et al., 2004)
Coating	SiO_2	Self-cleaning; fire retardant	(Jones et al., 2017; Van Broekhuizen et al., 2011)
	TiO_2	Self-cleaning; hydrophobic properties	(Van Broekhuizen et al., 2011)
	Ag	Biocidal activity	(Kumar et al., 2008)
Steel	Cu	Weldability; corrosion resistance; formability	(Ge and Gao, 2008)
Solar cell	TiO_2	Non-utility electricity generation	(Zhu et al., 2004)
	CNTs	Effective electron mediation	(Zhang et al., 2006)

2.1. Nano-silica (nano-SiO_2)

Nano-silica has been proven effective for increasing the compressive strength of concrete at an early age, thereby improving concrete workability and durability (Li et al., 2004; Sobolev et al., 2009; Saleh et al., 2018) and increasing resistance to water penetration (Ji, 2005). Moreover, nano-silica hastens the hydration reaction of both tricalcium silicate and ash cement mortar (Ji, 2005; Jo et al., 2007; Li et al., 2006a) and controls the leaching of calcium in water (Spitzmiller et al., 2013). In addition, nano-silica improves the strength of concrete more efficiently than micro-silica (Jo et al., 2007; Li et al., 2004;

Sobolev et al., 2009). Some research has stated that nano-silica acts as an activator to boost pozzolanic reactions and as a filler to improve the microstructure (Jo et al., 2007). Nano-silica can also improve the segregation resistance of self-compacting concrete (Bigley and Greenwood, 2003).

Glass coated with nano-silica can be used as fireproof windows in buildings and as antireflection glass to reduce building energy consumption by controlling exterior light (Rana et al., 2009). Moreover, nano-silica can be used as a coating material to make tile, stone, and wood surfaces resistant to water, corrosion, and scratching (Caldarelli et al., 2015; Kumar et al., 2015; Nakajima et al., 2014; Wang et al., 2015).

2.2. Nano-titania (nano-TiO_2)

Nano-titania is very effective for self-cleaning and depolluting concrete (Sanchez and Sobolev, 2010). Concrete containing nano-titania generates a photocatalytic degradation of pollutants and aldehydes (Chen and Poon, 2009). Nano-titania is also spread onto surfaces and through their volume incorporation into asphalt mixtures with tailored photocatalytic properties. Utilizing nano-titania can also significantly decrease the maintenance costs of high-rise building façades due to its self-cleaning properties (Carneiro et al., 2013). A self-cleaning glass based on nano-titania cleans itself easily. The photocatalytic process disintegrates organic dirt on the glass with ultraviolet light and makes the glass superhydrophilic through a powerful catalytic reaction. Subsequently, water washes away the dirt (Arafa and DeFazio, 2006) leaving no streaks because the water spreads evenly on the superhydrophilic surface (Cannavale et al., 2010; Chen and Poon, 2009; Drelich et al., 2011). Nano-titania is photoactivated by ultraviolet light to yield reactive oxygen species, which effectively remove dirt and bacterial films from any surfaces such as walls, pavements, roofs, and glass (Irie et al., 2004). However, a small amount of silver added to the nano-titania can improve its antibacterial effects without ultraviolet light irradiation (Boostani and Modirrousta, 2016). As well as its self-cleaning properties, a number of studies have illustrated that nano-titania can boost the Portland cement hydration process (Jayapalan et al., 2009), improve concrete abrasion resistance, and increase the flexural and compressive strength of concrete (Li et al., 2006a; Li et al., 2007b).

2.3. Nano-ferric oxide (nano-Fe_2O_3)

Nano-ferric oxide has been claimed to provide concrete with self-sensing capabilities and enhance its flexural and compressive strength (Li et al., 2004). Moreover, cement mortar with nano-ferric oxide can determine its own compressive stress due to changes in its volume electric resistance with an applied load (Sanchez and Sobolev, 2010). This potential is indispensable for the development and building of smart structures and real-time structural health monitoring and damage detection as it removes the need to attach or embed sensors.

2.4. Carbon nanotubes (CNTs)

CNTs are cylindrical carbon molecules with exceptional chemical properties, which can be used as nano-reinforcements in concrete. CNTs can significantly enhance mechanical durability by gluing cementitious agents and aggregates (Ge and Gao, 2008; Hallock et al., 2009) and improve other physico-mechanical properties of concrete. CNTs are among the most effective nanomaterials for improving concrete properties and increasing its resistance to the propagation of cracks (Srivastava et al., 2003). The addition of small amounts of CNTs can efficiently prevent crack propagation in concrete composites (Spitzmiller et al., 2013). Meanwhile, more improvements can be achieved in the flexural and compressive strength of concrete by the oxidation of multi-walled CNTs (Mann, 2006). Carbon nanofibers are cheaper than CNTs (Kang et al., 2006) and more appropriate for mass production. Many studies have compared CNTs with carbon nanofibers incorporated with cement pastes (Konsta-Gdoutos et al., 2010); however, relatively few studies have investigated incorporating the CNTs into the mortar (Li et al., 2005; Li et al., 2007a). The incorporation of CNTs into non-decorative ceramics can decrease their fragility and improve their mechanical strength and thermal properties (Luo et al., 2004). Additionally, CNTs improve and accelerate the performance of solar cells (Brown and Kamat, 2008).

2.5. Other nanomaterials

Many studies (Chang et al., 2007; He and Shi, 2008; Morsy et al., 2009) have proven that nano-clay improves concrete resistance to chloride penetration, mechanical performance, and self-compacting properties, as well as decreasing shrinkage and permeability. Nano-alumina (nano-Al_2O_3) notably increases the concrete elasticity modulus, however, it has a small effect on its compressive strength (Li et al., 2006b). The incorporation of copper (Cu) nanoparticles into steels can reduce surface unevenness, which can alleviate the number of stress risers and therefore fatigue cracking (Ge and Gao, 2008; Mann, 2006). Moreover, the application of calcium (Ca), magnesium (Mg), copper (Cu), and copper oxide (CuO) nanoparticles tends to improve steel weld toughness and weldability (Spitzmiller et al., 2013). In addition, the magnetic interaction of nickel (Ni) improves the mechanical properties of cement mortars and therefore increases concrete compressive strength by approximately 15% (Guskos et al., 2010). Silver (Ag) nanoparticles can also be mixed with paint to provide antimicrobial surfaces in operating theaters (Kumar et al., 2008).

3. Potential exposure to nanoparticles

The growing nanomaterial production rate has increased concerns about the release of nanoparticles into the environment. Nanoparticles can be released to the atmosphere, surface water, and soil as either bare or functionalized nanoparticles, as aggregates, or after embedding them within a matrix (Bystrzejewska-Piotrowska et al., 2009). It has been proven that nanoparticles can be released to the environment at different phases of their life cycle (Lee et al., 2010). Some researchers (Brown and Kamat, 2008; Liu et al., 2007) have also reported that nanoparticles can be released to the environment during their manufacture, transportation, utilization, and destruction. Released nanoparticles are dispersed throughout the environment when they reach the soil, water, and air, where they can persist or be taken up by biological organisms, representing an ecotoxicological hazard. Moreover, they experience bioaccumulation or biodegradation in the food chain (SCENIHR, 2006). Some nanoparticles should be considered as emerging pollutants (O'Brien and Cummins, 2008) due to their potential toxicity impacts related to their negative influences on human health and nature (Mann, 2006). Standard demolition procedures strongly suggest that a skilled specialist should be hired to supervise the disposal of hazardous materials such as asbestos cement, and lead paint, as well as the removal of nano-enabled products (coated windows and nano-sensors) prior to building demolition by heavy mechanical disruption (Kourmpanis et al., 2008).

To determine the risks of nanomaterials, a clear understanding of their potential exposure during construction activities is required. A number of factors such as the quantity and frequency of nanomaterial use and the probability of particle release during different phases of the construction process (construction, operation, refurbishment, demolition, and recycling) should be considered (Jones et al., 2017) in order to understand the exposure risks. Exposure to nanomaterials should be considered one of the greatest risks in the construction industry (Díaz-Soler et al., 2016). Recognizing and understanding these risks necessitates real-time exposure monitoring, which is far from simple. The exposure monitoring challenges, including differentiating between released and background particles, variations in measurement methodologies, and the complexity and immobility of some measuring equipment, have been widely discussed in the literature (Azami et al. 2015; Jones et al., 2017; Kuhlbusch et al., 2011; Kumar and Morawska, 2014; Van Broekhuizen et al., 2011). Moreover, the technical constraints of available sampling and analytical techniques may not allow the accurate detection of very low-level exposure levels (Schimpel et al., 2017).

One of the important aspects of typifying risks and avoiding accidental effects is an exposure evaluation. There are a number of proposed exposure scenarios during the nanomaterial life cycle that are simulated in the construction industry (Lee et al., 2010). One of the most comprehensive scenarios, which was developed by Lee et al. (2010), is illustrated in Fig. 2.

Nanomaterials can affect workers during manufacturing, on construction sites, and during disposal in demolition field processes. Moreover, residents can also be affected in the customer use process. Despite the risk of high exposure to biological, chemical, and ergonomic hazards (Jones et al., 2015), researchers have paid less attention to workers (Díaz-Soler et al., 2016), and toxicity hazard information remains limited for the construction industry (Krug, 2014; Valsami-Jones and Lynch, 2015). Fig. 3 shows the frequent routes of nanomaterial exposure and entry to the major organs (Kagan et al., 2010; Yokel and MacPhail, 2011).

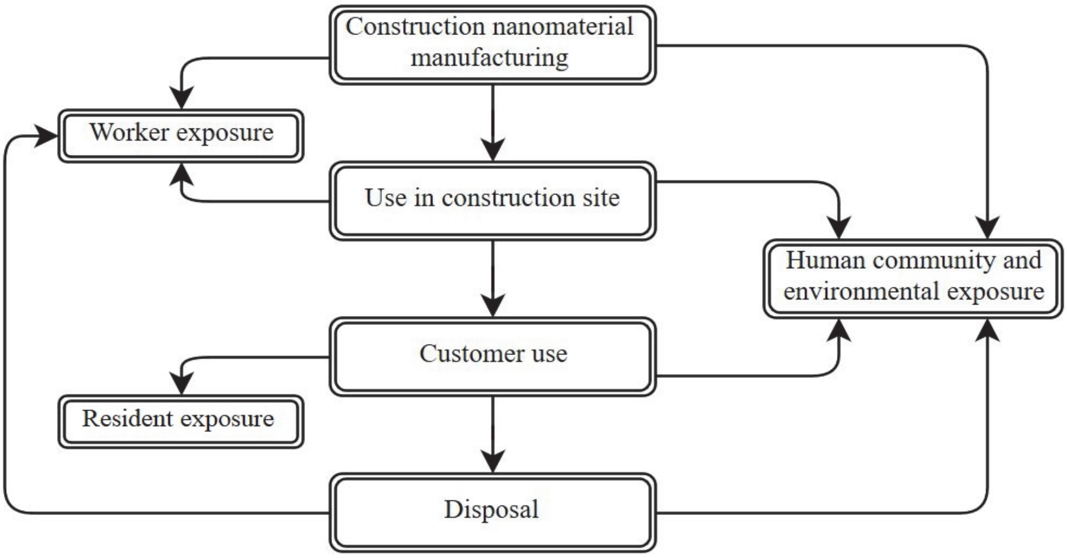

Fig. 2. Exposure scenarios of nanomaterials used in construction (Lee et al., 2010)

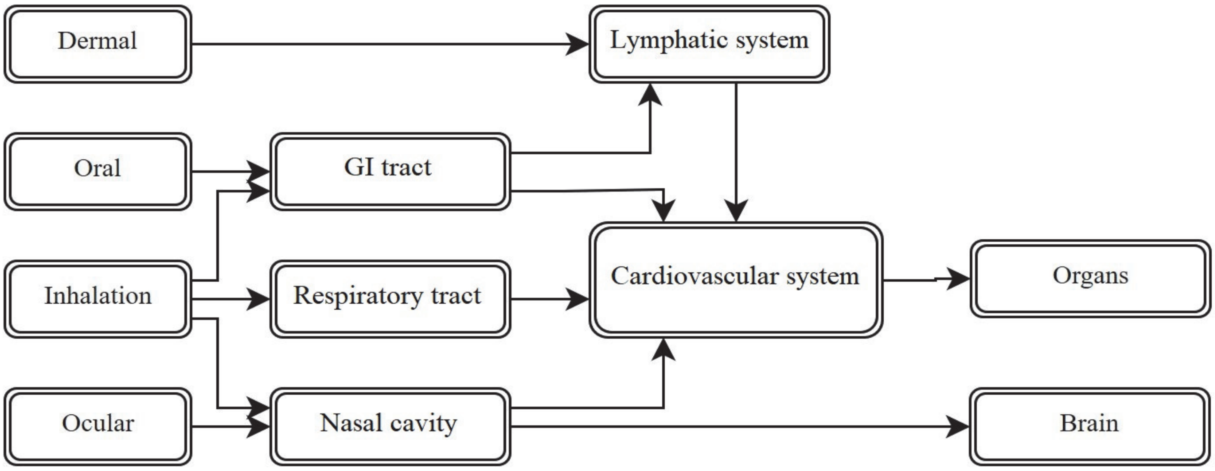

Fig. 3. Routes of nanomaterial exposure to human organs (Yokel and MacPhail, 2011)

4. Risk assessment of potential exposure to nanomaterials

Natural disasters (such as storms or heavy rainfall) and human accidents (such as fire) lead to damage to nano-enabled products in building elements, causing the release of nanoparticles into the environment. For instance, precipitation can cause nanoparticles to settle and penetrate into the soil and groundwater, and fire can release nanoparticles to the atmosphere. As a result of vague ingredient labels on nano-enabled construction products, exposure monitoring problems, and current analytical limitations, it is highly challenging to characterize these releases based on long-term activity (Jones et al., 2017; Liu et al., 2007) and map the affected areas. These difficulties include the limited detectability that prevents quantification of substances released from nanomaterials at a low rate as well as insufficient analytical specificity to recognize nanoparticle forms and concentrations in complicated environmental matrices (Lee et al., 2010). Furthermore, recent nanotoxicology research has provided a limited but increasing database; however, no standardized framework exists to evaluate and interpret these data (Kuempel et al., 2012). Thus, a strategic framework is required to thoroughly characterize nanomaterial hazards (Mattsson and Simko, 2017).

Therefore, to quantify the human exposure to nanomaterials, a qualitative risk assessment (control banding) was presented to control worker exposure and simplify potential exposure risk assessments (Zalk et al., 2009). Moreover, another risk management method was developed based on precautionary risk management to decrease the risk of exposure to nanomaterials for industry workers (Ling et al., 2012). In that study, nanomaterial risks were categorized based on aspect identification, solubility tests, dermal absorption, and cytotoxic analyses. Furthermore, another methodology was developed to create a real-life relevant risk profile for a given nanomaterial to identify which materials pose higher risks, where these risks appear in the life cycle, and the effect of these risks (Schimpel et al., 2017). Other research identified the key features of an integrated risk governance framework for nanotechnologies and described the tools required for this framework and their effective integration (Stone et al., 2018).

A number of activities in the construction industry increase the risk of exposure to nanomaterials such as cutting, sanding, drilling, and machining nano-enabled products, which all lead to inhalation risks (Jones et al., 2017). Nevertheless, if workers are not informed that they are working with products containing nanomaterials (for example, because of inadequate labeling), they cannot factor this into the risk management process. In addition, workers will not be able to take necessary precautions if unknown nano-enabled products exist in the site. Demolition is an obvious example, where it can be difficult to obtain detailed information on the ingredients of building elements (Jones et al., 2017).

Undoubtedly, current industrial health standards should be changed because the commonly used exposure index (mass per unit of volume) does not consider important toxicity parameters and conventional aerosol measurement techniques are not appropriate for evaluating exposure to nanomaterials (Oberdörster et al., 2005). Nanomaterial exposure could be in the form of inhalation, swallowing, or touching (Al-Bayati and Al-Zubaidi, 2018). Breathing nanomaterials during production, molding, coating, and incorporation can pose a serious health problem to workers; thus, air quality monitoring is required during the production process of nanomaterials in a factory. Moreover, in addition to personal shielding equipment (masks, gloves, and overalls) used to mitigate the possible hazard, a regular medical check is also strongly recommended for workers (Lee et al., 2010; Spitzmiller et al., 2013) because even the recommended personal shielding equipment may not be sufficient. For example, HEPA filters are recommended for workers who are exposed to nanomaterials however, these filters do not adequately remove particles measuring less than 300 nm in diameter (Al-Bayati and Al-Zubaidi, 2018). A number of preventive and protective measures have been presented with regard to the nanomaterial properties. For example, Díaz-Soler et al. (2016) described five key action steps for managing exposure to nanomaterials in construction areas, in addition, to the conventional industrial hygiene process.

In nanotechnology, similar to any other emerging technology, regulators are still one step behind the technology. For example, there is no regulation in the US to enforce producers to include nanoparticle information in the product safety data sheet (West et al., 2016), and the US Occupational Safety and Health Administration does not provide mandatory exposure limits to alleviate the possible hazards of nanomaterials (Al-Bayati and Al-Zubaidi, 2018). To enable regulators to prepare comprehensive and beneficial rules and regulations for nanotechnology in general and nano-enabled products in the construction industry in particular, it is crucial to first identify the lack of knowledge regarding nanomaterial use, potential exposure pathways, and possible toxicological hazards. Therefore, an advanced version of the "known knowns and unknown unknowns" model has been developed to explore and address the areas where intervention is most required (Jones et al., 2017).

5. Toxicity and adverse biological effects of nanomaterials

According to previous literature, the toxic effects of most nanomaterials commonly used in the construction industry are summarized in Table 2 and their associated health problems are illustrated in Fig. 4. Although this information on nanomaterial toxicity is available in the literature, it is not broadly accessible to decision makers, regulatory authorities, workers and end-users.

An important aspect of nanomaterial use in the construction industry is the virulence factor, which describes the disease-causing ability of these materials and their effect on human health. Nanomaterials pose a toxicological risk to microorganisms and higher organisms through DNA damage and cell wall disruption. Many studies have evaluated and assessed the bioaccumulation and toxicity impacts of nanomaterials in different organisms (Lopez-Serrano et al., 2014). Although some researchers believe that the size of nanomaterials is the dominant factor controlling their effects on human health (Gehr et al., 2006), toxicologists have claimed that this is only one of several factors (Krug and Klug, 2008). In comparison with bulk materials, nanomaterials have more convoluted physico-chemical properties, including their size, surface area, shape, crystallinity, porosity, and colloidal stability. These complex properties could have a noticeable effect on their interaction with physiological barriers (Meng et al., 2018). Nanomaterials pose a toxicological risk to human organisms via multiple mechanisms. These mechanisms include cell wall disruption, production of reactive oxygen species (ROS) that cause oxidative stress, DNA damage, release of toxic metals, and direct oxidation on contact with cell constituents (Lee et al., 2010). In most previous research on the safety of nanomaterials, a conventional material-by-material approach has been employed in order to appraise ROS production, DNA damage, and cytotoxicity. Nevertheless, a dramatic improvement is required to develop evaluation approaches that more closely reflect nanomaterial mechanisms under possible exposure scenarios (Collins et al., 2017).

Nano-silica is generally amorphous, which is less toxic than its crystalline form; however, it has been reported as a human carcinogen (IARC, 1997). Carcinogens are any substances that are directly involved in causing cancer. Exposure to crystalline nano-silica in workplaces may cause silicosis in workers and lead to lung cancer and tuberculosis (Leung et al., 2012). Nano-silica particles pose a toxicity risk by inducing oxidative stress (Wang et al., 2009; Ye et al., 2010a; Ye et al., 2010b), lipid peroxidation, and membrane damage (Lin et al., 2006) by blocking apoptosis; i.e., programmed cell death, which automatically eliminates the functionality of defective cells. Blocking apoptosis results in the production of tumor cells, which leads to cancer (Van Broekhuizen et al., 2011). Oxidative stress may result in immunotoxicity, autophagy, endothelial dysfunction, and neurotoxicity (Murugadoss et al., 2017). This type of nanomaterial may alsoresult in genotoxicity through DNA damage, interaction with DNA, and changes in gene expression (Donaldson et al., 2010). Under high exposure to nano-silica, inflammatory or cytotoxic effects have nanomaterial has been reported (Jones et al., 2017).

Inhalation of high doses of nano-titania may cause moderate inflammation of the lungs (Jones et al., 2017). Nano-titania irradiated with sunlight generates ROS that induce cytotoxicity, inflammation, and DNA damage in mammalian cells (Handy et al., 2008; Reeves et al., 2008). Rapid production of ROS causes oxidative stress in human cells, which can cause a wide range of diseases such as Parkinson's and Alzheimer's and result in severe damage to the liver and kidneys (Zhao et al., 2010).

The acute toxicity of nano-titania has been tested on laboratory animals and been found to induce negative effects including proliferation of epithelial cells in the lungs and lymph nodes, inflammation, and squamous metaplasia; however, those tests were conducted under relatively high exposure and these effects are unlikely to occur in practice. (Shakeel et al., 2016). The shape of the titania molecule facilitates its penetration of the cell through the cell membrane and also its motility inside the cell. When nano-titania reaches the blood stream, it may pass through the blood-testis barrier and result in sperm malformation, testicular lesions, and changes in serum sex hormone levels (Gao et al., 2013).

Table 2. Toxic effects of commonly used nanomaterials in the construction industry

Nanoparticle	*Toxic effect*	*References*
SiO_2	ROS toxicity; toxic to marine algae; apoptosis; upregulation of tumor necrosis factor; inflammatory responses; human carcinogens; genotoxicity	(Attik et al. 2008; Dutta et al. 2007; Fujiwara et al. 2008; Jones et al., 2017; Murugadoss et al., 2017; Van Broekhuizen et al., 2011; Wang et al. 2010; Ye et al., 2010a; Ye et al., 2010b)
TiO_2	Acute lethality; growth inhibition; bactericidal for Gram-positive bacteria; suppression of photosynthetic activity; oxidative damage due to ROS; inflammation in lungs	(Aruoja et al. 2009; Blaise et al. 2008; Kasemets et al. 2009; Rincón and Pulgarin 2004b; Zhao et al., 2010)
CNTs	Antibacterial; cell membrane damage; apoptosis/necrosis; inhibition of respiratory functions; mitochondrial DNA damage; granulomas and atherosclerotic lesions; inhibition of bacterial clearance from the lung tissues	(Blaise et al. 2008; Dong et al. 2009; Ema et al., 2016; Kang et al. 2007; Knief et al. 2009; Kobayashi et al., 2017; Liu et al. 2009)
Cu/CuO	Toxic to freshwater algae and yeast; DNA damage; lipid peroxidation; acute toxicity to liver, kidney and spleen; necrosis of hepatocytes	(Aruoja et al. 2009; Blaise et al. 2008; Kasemets et al. 2009; Midander et al. 2009)

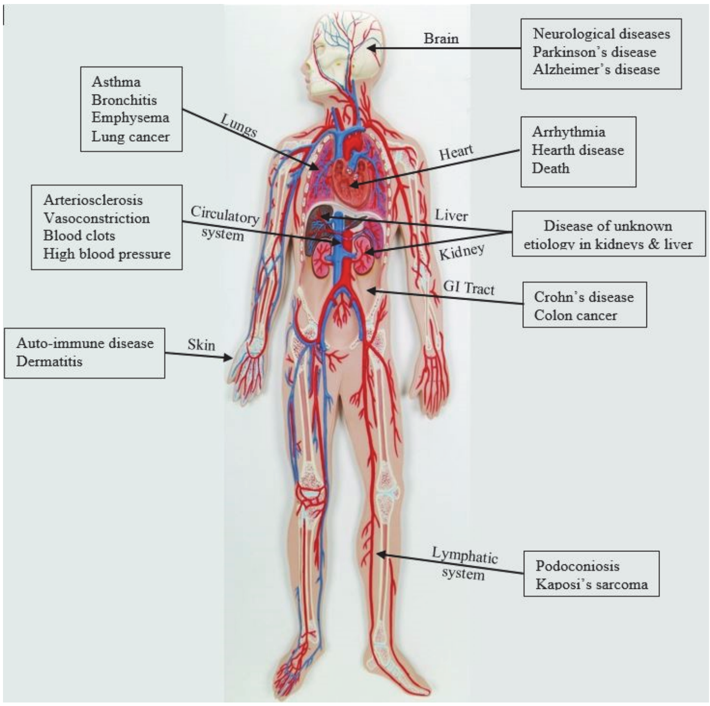

Fig. 4. Human body organs affected by nanoparticles and the associated diseases (Pacheco-Blandino et al., 2012)

Despite these hazards, solar irradiation facilitates titania antimicrobial activity toward different bacteria, including *Escherichia coli*, *Micrococcus luteus*, *Bacillus subtilis,* and fungi such as *Aspergillus niger* (Rincón and Pulgarin, 2004a; Rincón and Pulgarin, 2004b).

In an article comparing the similarities and differences between asbestos and CNTs, the authors claimed that any bio-persistent fibers longer than 5 µm in length and less than 1 µm in diameter can easily penetrate deep into the lung and the protective mechanisms of body are not able to break them down; therefore, these fibers are particularly problematic (Donaldson et al., 2013). Inhalable sizes of CNTs can cause problems to human health by inducing pulmonary toxicity (fibrosis, epithelioid, or inflammation) in humans (Kobayashi et al., 2017; Wei et al., 2007). When CNTs are phagocytized by alveolar macrophages, alveolar macrophages release chemokines and inflammatory cytokines into the lungs, which lead to fibrosis and respiratory cancer (Nishi et al., 2009; Ogami et al., 2007). A number of in vivo studies clearly show that malignant mesothelioma is the result of CNT inhalation (Takagi et al., 2008), which was found to be akin to asbestos (Lin et al., 2013b; Zhang et al., 2016). It has been claimed that exposure to CNTs during pregnancy may induce teratogenicity and developmental toxicity in fetus (Ema et al., 2016). The carcinogenicity of CNTs has been predominantly investigated in laboratory animals and there have been no attempts to evaluate it on humans (Kobayashi et al., 2017); therefore, this represents a potential topic for further research. CNTs also show antibacterial properties, cell wall damage (Kang et al., 2007; Kang et al., 2009), and oxidative stress (Kang et al., 2008). The cell wall is one of the most important supportive and protective structures in mammal cells. Disruption of the cell wall can result in penetration of disease-causing particles into the cell. In addition, DNA damage in human cells is a known negative impact of utilizing copper and copper oxide nanoparticles (Blaise et al. 2008; Lee et al., 2008).

6. Conclusions

Among the many beneficial applications of nanomaterials in the construction industry, these materials can also be employed to increase energy saving in buildings. For example, CNTs can be used to enhance the efficiency of energy transmission, heating, and lighting systems. Moreover, nano-silica can be utilized in isolating ceramics, coating, and paint to improve building thermal properties and energy performance. In addition, nanomaterials have the ability to increase building durability by improving fatigue, abrasion, and resistance to corrosion, which can lead to an indirect decrease in energy consumption and total costs in the construction industry. Thus, nanomaterials are likely to be the main choice for certain construction materials due to their novel and extraordinary properties. However, there are still concerns about their unknown effects on human, ecological, and environmental health. These points of concern have prompted a wide range of research on evaluating nanomaterial risk factors, as well as studies on the safe production, biological limits, and safe handling of nanomaterials from production to dumping and disposal. However, research on identifying, assessing and managing the associated risk factors have not developed at the same rate at which nanotechnology has been developing.

Nanomaterials can cause pulmonary malfunctions, which are a major symptom of respiratory problems along with skin irritation; however, the mechanism of their disease-causing abilities has not been fully revealed. For this reason, substantial research has attempted to determine the mechanistic relationship between the structure and reactivity of nanomaterials and their connection to the human immune system and cell toxicity. These studies not only reflect the acute phase of toxicity and mortality but also address the influence of sub-lethal continuous exposure on living organisms. Despite multiple studies on the potential hazards of nanomaterials, the consequences of their associated risks remain unclear. Another issue is the inadequate toxicity information on the level of nanomaterial exposure for workers, end-users, and the environment. It is for these reasons that the manufacturers of nanomaterials and nano-enabled products should analyze the potential toxicity of their products and provide detailed safety data sheets. Due to their possible toxicity, it is critical for workers to know which nanoparticles they are exposed to. It is also crucial for risk analysts to understand the type and exact amount of nanoparticles in those products in order to prepare appropriate and effective risk management strategies to mitigate their undesirable effects.

Present analytical approaches are inadequate for measuring and distinguishing the formation of relatively low biological and ecological concentrations of nanomaterials in complex matrices. Consequently, improved analytical methods should be developed to determine the transport, conversion, mechanism, and fate of nanomaterials in a variety of biological and ecological fields. Advanced techniques would enable the short-term monitoring of laborers exposed to the effects of nanomaterials during manufacture, building, and destruction as well as long-term observations of the material itself. Material observations should include monitoring the release of nanoparticles from nano-enabled construction products by different mechanisms, such as aging, erosion, corrosion, and exposure to different weather conditions.

Similar to the pharmaceutical industry, where drugs with serious side effects are accepted for use in life-threatening diseases such as cancer, nano-enabled products should be considered for use in the construction industry only after a comprehensive risk-benefit analysis. It is clear that nanomaterials offer many potential benefits; nevertheless, those benefits should be balanced against their potential hazards. Silver nanoparticles are a good example. It can be mixed with paint to provide an antimicrobial surface for use in operating theaters; however, as a result of its toxicity to microbes, it may influence the development of resistant microorganisms. Furthermore, lack of knowledge might adversely affect risk-benefit analyses. A clear example of this is asbestos, which represents historical evidence of a risk-benefit balance failure. Therefore, further comprehensive research should be conducted into the potential hazards of nanoparticles before performing any risk-benefit analysis.

In conclusion, we believe that the following steps should be undertaken in order to safely derive the maximum benefit from nanomaterials.

- Comprehensive research studies should be conducted to fill the knowledge gap related to the toxicity of available and emerging nanomaterials to human and organisms.
- Manufacturers of nanomaterials and nano-enabled products should be rigorously enforced to declare all nanoparticle ingredients in their products.
- Safety data sheets should be provided with all nano-enabled products and should be made available to everyone who has contact with those products.
- An extensive risk-benefit analysis should be performed before commercialization and industrialization of any nanoparticles.
- Risk assessment methodologies should be developed in order to consider all potential risks during the life cycle of nanomaterials and nano-enabled products.

References

Aguar-Fernandez M.P., Hullmann A., (2007), A boost for safer nanotechnology, *Nano Today,* **2**, 56.

Aguiar F.P., Espinola J.G.P., Fonseca M.G., Arakaki L.N.H., Teotonio E.E.S., de Oliveira S.F., (2017), Silica gel modified with amino imine groups as an adsorbent for metallic cations, *Environmental Engineering and Management Journal,* **16**, 213-224.

Al-Bayati A.J., Al-Zubaidi H.A., (2018), Inventory of nanomaterials in construction products for safety and health, *Journal of Construction Engineering and Management*, **144**, 060180041-060180044.

Arafa M.D., DeFazio C., (2006), *Nano-composite Coatings for Transportation Infrastructures: Demonstration Projects*, In: *NICOM 2: 2nd International Symposium on Nanotechnology in Construction*, Miguel Y., Porro A., Bartos P.J.M. (Eds.), RILEM Publications, Bilbao, 363-371.

Arico A.S., Bruce P., Scrosati B., Tarascon J.M., Schalkwijk W., (2005), Nanostructured materials for advanced energy conversion and storage devices, *Nature Materials*, **4**, 366-377.

Aruoja V., Dubourguier H.C., Kasemets K., Kahru A., (2009), Toxicity of nanoparticles of CuO, ZnO and TiO_2 to microalgae Pseudokirchneriella subcapitata, *Science of the Total Environment*, **407**, 1461-1468.

Attik G., Brown R., Jackson P., Creutzenberg O., Aboukhamis I., Rihn B.H., (2008), Internalization, cytotoxicity, apoptosis, and tumor necrosis factor-alpha expression in rat alveolar macrophages exposed to various dusts occurring in the ceramics industry, *Inhalation Toxicology*, **20**, 1101-1112.

Azami F., Kumar P., Mulheron M., Colaux J.L., Jeynes C., Adhami S., Watts J.F., (2015), Physicochemical characterstics and occupational exposure to coarse, fie and ultrafine particles during building refurbishment activities, *Journal of Nanoparticle Research*, **17**, 1-19.

Baetens R., Jelle B.P., Gustavsen A., (2011), Aerogel insulation for building applications: A state-of-the-art review, *Energy and Buildings*, **43**, 761-769.

Bartos P.J.M., (2014), Editorial: photocatalytic concrete, *Magazine of Concrete Research*, **66**, 217-218.

Beaudrie C.E.H., Kandlikar M., Gregory R., Long G., Wilson T., (2015), Nanomaterial risk screening: a structured approach to aid decision making under uncertainty, *Environment Systems and Decisions*, **35**, 88-109.

Bergamaschi E., Murphy F., Poland C.A., Mullins M., Costa A.L., McAlea E., Tran L., Tofail S.A.M., (2015), Impact and effectiveness of risk mitigation strategies on the insurability of nanomaterial production: Evidences from industrial case studies, *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology*, **7**, 839-855.

Bigley C., Greenwood P., (2003), Using silica to control bleed and segregation in self-compacting concrete, *Concrete*, **37**, 43-45.

Blaise C., Gagné F., Férard J.F., Eullaffroy P., (2008), Ecotoxicity of selected nano-materials to aquatic organisms, *Environmental Toxicology*, **23**, 591-598.

Boostani H., Modirrousta S., (2016), Review of Nanocoatings for Building Application, *Procedia Engineering*, **145**, 1541-1548.

Brown P., Kamat P.V., (2008), Quantum dot solar cells Electrophoretic deposition of CdSe-C60 composite films and capture of photogenerated electrons with nC60 cluster shell, *Journal of the American Chemical Society*, **130**, 8890-8891.

Bystrzejewska-Piotrowska G., Golimowski J., Urban P.L., (2009), Nanoparticles: Their potential toxicity, waste and environmental management, *Waste Management*, **29**, 2587-2595.

Caldarelli A., Raimondo M., Veronesi F., Boveri Giulio., Guarini G., (2015), Sol-gel route for the building up of superhydrophobic nanostructured hybrid-coatings on copper surfaces, *Surface and Coatings Technology*, **276**, 408-415.

Cannavale A., Fiorito F., Manca M., Tortorici G., Cingolani R., Gigli G., (2010), Multifunctional bioinspired sol-gel coatings for architectural glasses, *Building and Environment*, **45**, 1233-1243.

Carneiro J.O., Azevedo S., Teixeira V., Fernandes F., Freitas E., Silva H., Oliveria J., (2013), Development of photocatalytic asphalt mixtures by the deposition and volumetric incorporation of TiO_2 nanoparticles, *Construction and Building Materials*, **38**, 594-601.

Chang T.-P., Shih J.-Y., Yang K.-M., Hsiao T.-C., (2007), Material properties of Portland cement paste with nano-montmorillonite, *Journal of Materials Science*, **42**, 7478-7487.

Chen J., Poon C., (2009), Photocatalytic construction and building materials: From fundamentals to applications, *Building and Environment*, **44**, 1899-1906.

Chuah S., Pan Z., Sanjayan J.G., Wang C.M., Duan W.H., (2014), Nano reinforced cement and concrete composites and new perspective from graphene oxide, *Construction and Building Materials*, **73**, 113-124.

Collins A.R., Annangi B., Rubio L., Marcos R., Dorn M., Merker C., Estrela-Lopis I., Cimpan M.R., Ibrahim M., Cimpan E., Ostermann M., Sauter A., Yamani N.E., Shaposhnikov S., Chevillard S., Paget V., Grall R., Delic J., de-Cerio F.G., Suarez-Merino B., Fessard V., Hogeveen K.N., Fjellsbø L.M., Pran E.R., Brzicova T., Topinka J., Silva M.J., Leite P.E., Ribeiro A.R., Granjeiro J.M., Grafström R., Prina-Mello A., Dusinska M., (2017), High throughput toxicity screening and intracellular detection of nanomaterials, *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology*, **9**, 1413-1443.

Dai L., (2006), *Carbon Nanotechnology: Recent Developments in Chemistry, Physics, Materials Science and Device Applications*, 1st Edition, Elsevier Science, Amsterdam.

Díaz-Soler B.M., Martínez-Aires M.D., López-Alonso M., (2016), Emerging risk in the construction industry: Recommendations for managing exposure to nanomaterials, *Dyna*, **83,** 48-54.

Donaldson K., Poland C.A., Murphy F.A., MacFarlane M., Chernova T., Schinwald A., (2013), Pulmonary toxicity of carbon nanotubes and asbestos – Similarities and differences, *Advanced Drug Delivery Reviews*, **65**, 2078-2086.

Donaldson K., Poland C.A., Schins R.P.F., (2010), possible genotoxic mechanisms of nanoparticles: criteria for improved test strategies, *Nanotoxicology*, **4**, 414-420.

Dong L., Witkowski C.M., Craig M.M., Greenwade M.M., Joseph K.L., (2009), Cytotoxicity effects of different surfactant molecules conjugated to carbon nanotubes on human astrocytoma cells, *Nanoscale Research Letters*, **4**, 1517-1523.

Drelich J., Chibowski E., Meng D.D., Terpilowski K., (2011), Hydrophilic and superhydrophilic surfaces and materials, *Soft Matter*, **7**, 9804-9828.

Dutta D., Sundaram S.K., Teeguarden J.G., Riley B.J., Filfiled L.S., Jacobs J.M., Addleman S.R., Kaysen G.A., Moudgil B.M., Weber T.J., (2007), Adsorbed proteins influence the biological activity and molecular targeting of nanomaterials, *Toxicological Sciences*, **100**, 303-315.

Ema M., Hougaard K.S., Kishimoto A., Honda K., (2016), Reproductive and developmental toxicity of carbon-based nanomaterials: a literature review, *Nanotoxicology*, **10**, 391-412.

Fujiwara K., Suematsu H., Kiyomiya E., Aoki M., Sato M., Moritoki N., (2008), Size-dependent toxicity of silica nano-particles to Chlorella kessleri, *Journal of Environmental Science and Health-Part A-Toxic/Hazardous Substances and Environmental Engineering*, **43**, 1167-1173.

Gao G., Ze Y., Zhao X., Sang X., Zheng L., Ze X., Gui S., Sheng L., Sun Q., Hong J., Yu X., Wang L., Hong F., Zhang X., (2013), Titanium dioxide nanoparticle-induced testicular damage, spermatogenesis suppression, and gene expression alterations in male mice, *Journal of Hazardous Materials*, **258-259**, 133-143.

Gao K., Lin K.L., Hwang C.L., Tuan B.L.A., Cheng T.W., Wang D., (2018), Elucidating the effects of nanosilica on the characteristics of alkali-activated thin-film transistor liquid-crystal display waste glass, *Environmental Engineering and Management Journa*l, **17**, 293-306.

Ge Z., Gao Z., (2008), *Applications of Nanotechnology and Nanomaterials in Construction*, Proc. First Int. Conf. on construction in developing countries, Karachi, 4-5.

Gehr P., Blank F., Rothen-Rutishauser B.M., (2006), Fate of inhaled particles after interaction with the lung surface, *Paediatric Respiratory Reviews*, **7**, 73-75.

Guskos N., Zolnierkiewicz G., Typek J., Blyszko J., Kiernozycki W., Narkiewicz U., (2010), Ferromagnetic resonance and compressive strength study of cement mortars containing carbon encapsulated nickel and iron nanoparticles, *Reviews on Advanced Materials Science*, **23**, 113-117.

Hallock M.F., Greenley P., DiBerardinis L., Kallin D., (2009), Potential risks of nanomaterials and how to safely handle materials of uncertain toxicity, *Journal of Chemical Health and Safety*, **16**, 16-23.

Handy R.D., Henry T.B., Scown T.M., Johnston B.D., Tyler C.R., (2008), Manufactured nanoparticles: Their uptake and effects on fish - A mechanistic analysis, *Ecotoxicology*, **17**, 396-409.

Hanus M.J., Harris A.T., (2013), Nanotechnology innovations for the construction industry, *Progress in Materials Science*, **58**, 1056-1102.

He X., Shi X., (2008), Chloride Permeability and Microstructure of Portland Cement Mortars Incorporating Nanomaterials, *Transportation Research Record: Journal of the Transportation Research Board*, **2070**, 13-21.

Hochmannova L., Vytrasova J., (2010), Photocatalytic and antimicrobial effects of interior paints, *Progress in Organic Coatings*, **67**, 1-5.

IARC, (1997), *Silica, Some Silicates, Coal Dust and para-Aramid Fibrils*, The International Agency for Research on Cancer, Lyon, France

Irie H., Sunada K., Hashimoto K., (2004), Recent developments in TiO_2 photocatalysis: Novel applications to interior ecology materials and energy saving systems, *Electrochemistry*, **72**, 807-812.

Jayapalan A.R., Lee B.Y., Kurtis K.E., (2009), *Effect of Nano-sized Titanium Dioxide on Early Age Hydration of Portland Cement*. In: *Nanotechnology in Construction 3*, Bittnar Z., Bartos P.J.M., Němeček J., Šmilauer V., Zeman J. (Eds.), Springer, Berlin, Heidelberg, 267-273.

Ji T., (2005), Preliminary study on the water permeability and microstructure of concrete incorporating nano-SiO_2, *Cement and Concrete Research*, **35**, 1943-1947.

Jo B.-W., Kim C.-H., Tae G., Park J.-B., (2007), Characteristics of cement mortar with nano-SiO_2 particles, *Construction and Building Materials*, **21**, 1351-1355.

Jones W., Gibb A., Goodier C., Bust P., (2017), managing the unknown – Addressing the potential health risks of nanomaterials in the built environment, *Construction Management and Economics*, **35**, 122-136.

Jones W., Gibb A., Goodier C., Bust P., Jin J., Song M., (2015), Nanomaterials in construction and demolition - how can we assess the risk if we don't know where they are? *Journal of Physics: Conference Series*, **617**, 12031-12039.

Ju-Nam Y., Lead J.R., (2008), Manufactured nanoparticles: An overview of their chemistry, interactions and potential environmental implications, *Science of the Total Environment*, **400**, 396-414.

Justo-Hanani R., Dayan T., (2015), European risk governance of nanotechnology: Explaining the emerging regulatory policy, *Research Policy*, **44**, 1527-1536.

Kagan V., Shi J., Feng W., Shvedova A.A., Fadeel B., (2010), Fantastic voyage and opportunities of engineered nanomaterials: What are the potential risks of occupational exposures? *Journal of Occupational and Environmental Medicine*, **52,** 943-946.

Kang I., Heung Y.Y., Kim J.H., Lee J.W., Gollapudi R., Subramaniam S., Narasimhadevara S., Hurd D., Kirikera G.R., Shanov V., Schulz M.J., Shi D., Boerio J., Mall S., Ruggles-Wren M., (2006), Introduction to carbon nanotube and nanofiber smart materials, *Composites Part B: Engineering*, **37**, 382-394.

Kang S., Herzberg M., Rodrigues D.F., Elimelech M., (2008), Antibacterial effects of carbon nanotubes: size does matter! *Langmuir*, **24**, 6409-6413.

Kang S., Mauter M.S., Elimelech M., (2009), Microbial cytotoxicity of carbon-based nanomaterials: implications for river water and wastewater effluent, *Environmental Science & Technology*, **43**, 2648-2653.

Kang S., Pinault M., Pfefferle L.D., Elimelech M., (2007), Single-walled carbon nanotubes exhibit strong antimicrobial activity, *Langmuir*, **23**, 8670-8673.

Kasemets K., Ivask A., Dubourguier H.C., Kahru A., (2009), Toxicity of nanoparticles of ZnO, CuO and TiO_2 to yeast *Saccharomyces cerevisiae*, *Toxicology in Vitro*, **23**, 1116-1122.

Kim J.H., Scialli A.R., (2011), Thalidomide: The Tragedy of Birth Defects and the Effective Treatment of Disease, Tox*icological Sciences*, **122**, 1-6.

Knief P., Clarke C., Herzog E., Davoren M., Lyng F.M., Meade A.D., Byrne H.J., (2009), Raman spectroscopy--a potential platform for the rapid measurement of carbon nanotube-induced cytotoxicity, *Analyst*, **134**, 1182-1191.

Kobayashi N., Izumi H., Morimoto Y., (2017), Review of toxicity studies of carbon nanotubes, *Journal of Occupational Health*, **59**, 394-407.

Konsta-Gdoutos M.S., Metaxa Z.S., Shah S.P., (2010), Multi-scale mechanical and fracture characteristics and early-age strain capacity of high-performance carbon nanotube/cement nanocomposites, *Cement and Concrete Composites*, **32**, 110-115.

Kontos A.I., Kontos A.G., Tsoukleris D.S., Vlachos G.D., Falaras P., (2007), Superhydrophilicity and photocatalytic property of nanocrystalline titania sol-gel films, *Thin Solid Films*, **515**, 7370-7375.

Kourmpanis B., Papadopoulos A., Moustakas K, Stylianou M., Haralambous K.J., Loizidou M., (2008), Preliminary study for the management of construction and demolition waste, *Waste Management & Research*, **26**, 267-275.

Krug H.F., (2014), Nanosaftey research-Are we on the right track? *Angewandte Chemie International Edition*, **53**, 12304-12319.

Krug H.F., Klug P., (2008), *Impact of Nanotechnological Developments on the Environment*, In: *Nanotechnology: Environmental Aspects*, Krug H.F. (Eds.), Wiley-VCh, Weinheim, 291-306.

Kuempel E.D., Geraci C.L., Schulte P.A., (2012), Risk assessment and risk management of nanomaterials in the workplace: Translating research to practice, *Annals of Occupational Hygiene*, **56**, 491-505.

Kuhlbusch T.A.J., Asbach C., Fissan H., Gohler D., Stintz M., (2011), Nanoparticle exposure at nanotechnology workplace: A review, *Particle and Fiber Toxicology*, **8**, 22-40.

Kumar A., Vemula P.K., Ajayan P.M., John G., (2008), Silver-nanoparticle-embedded antimicrobial paints based on vegetable oil, *Nature Materials*, **7**, 236-241.

Kumar D., Wu X., Fu Q., Ho J.W.C., Kanhere P.D., Li L., Chen Z., (2015), Hydrophobic sol-gel coatings based on polydimethylsiloxane for self-cleaning applications, *Materials & Design*, **86**, 855-862.

Kumar P., Morawska L., (2014), Recycling concrete: an undiscovered source of ultrafine particles, *Atmospheric Environment*, **90**, 51-58.

Lee J., Mahendra S., Alvarez P.J.J., (2010), Nanomaterials in the construction industry: A review of their applications and environmental health and safety considerations, *ACS Nano*, **4**, 3580-3590.

Lee W.M., An Y.J., Yoon H., Kweon H.S., (2008), Toxicity and bioavailability of copper nanoparticles to the terrestrial plants mung bean (*Phaseolus radiatus*) and wheat (*Triticum aestivum*): plant agar test for water-insoluble nanoparticles, *Environmental Toxicology and Chemistry*, **27**, 1915-1921.

Leung C.C., Yu I.T., Chen W., (2012), Sillicosis, *The Lancet*, **379**, 2008-2018.

Li G.Y., Wang P.M., Zhao X., (2005), Mechanical behaviour and microstructure of cement composites incorporating surface-treated multi-walled carbon nanotubes, *Carbon*, **43**, 1239-1245.

Li G.Y., Wang P.M., Zhao X., (2007a), Pressure-sensitive properties and microstructure of carbon nanotube reinforced cement composites, *Cement and Concrete Composites*, **29**, 377-382.

Li H., Xiao H.G., Yuan J., Ou J., (2004), Microstructure of cement mortar with nano-particles, *Composites Part B: Engineering*, **35**, 185-189.

Li H., Zhang M., Ou J., (2007b), Flexural fatigue performance of concrete containing nano-particles for pavement, *International Journal of Fatigue*, **29**, 1292-1301.

Li H., Zhang M., Ou J., (2006a), Abrasion resistance of concrete containing nano-particles for pavement, *Wear*, **260**, 1262-1266.

Li Z., Wang H., He S., Lu S., Wang M., (2006b), Investigations on the preparation and mechanical properties of the nano-alumina reinforced cement composite, *Materials Letters*, **60**, 356-359.

Lin B., Zhang H., Lin Z., Fang Y., Tian L., Yang H., Yan J., Liu H., Zhang W., Xi Z., (2013b), Studies of single-walled carbon nanotubes-induced hepatotoxicity by NMR-based metabolomics of rat blood plasma and liver extracts, *Nanoscale Research Letters*, **8**, 236-246.

Lin J., Chen H., Fei T., Zhang J., (2013a), Highly transparent superhydrophobic organic-inorganic nanocoating from the aggregation of silica nanoparticles, *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, **421**, 51-62.

Lin W., Huang Y.W., Zhou X.D., Ma Y., (2006), Toxicity of cerium oxide nanoparticles in human lung cancer cells, *International Journal of Toxicology*, **25**, 451-457.

Ling M.P., Lin W.C., Liu C.C., Huang Y.S., Chueh M.J., Shih T.S., (2012), Risk management strategy to increase the safety of workers in the nanomaterials industry, *Journal of Hazardous Materials*, **229/230**, 83-93.

Liu R., Zhang Z., Zhong R., Chen X., Li J., (2007), Nanotechnology Synthesis Study: Research Report, Department of Electrical and Computer Engineering University of Houston, On line at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.123.9230&rep=rep1&type=pdf.

Liu S., Wei L., Hao L., Fang N., Chang M.W., Xu, R., Yang Y., Chen Y., (2009), Sharper and faster "nano darts" kill more bacteria: A study of antibacterial pristine single-walled carbon nanotube, *ACS Nano*, **3,** 3891-3902.

Lopez-Serrano A., Olivas R.M., Landaluze J.S., Camara C., (2014), Nanoparticles: a global vision. Characterization, separation, and quantification methods. Potential environmental and health impact, *Analytical Methods*, **6**, 38-56.

Luo T.Y., Liang T.X., Li C.S., (2004), Addition of carbon nanotubes during the preparation of zirconia nanoparticles: Influence on structure and phase composition, *Powder Technology*, **139**, 118-122.

Makhlouf A.S.H., Tiginyanu I., (2011), *Nanocoatings and Ultra-Thin Films: Technologies and Applications*, 1st Edition, Woodhead Publishing, Oxford Cambridge Philadelphia New Delhi.

Mann S., (2006), Nanoforum report on nanotechnology and construction, European Nanotechnology Gateway, On line at: https://nanotech.law.asu.edu/Documents/2009/10/Nanotech%20and%20Construction%20Nanoforum%20report_259_9089.pdf.

Mattsson M.O., Simko M., (2017), The changing face of nanomaterials: Risk assessment challenges along the value chain, *Regulatory Toxicology and Pharmacology*, **84**, 105-115.

Meng H., Leong W., Leong K.W., Chen C., Zhao Y., (2018), Walking the line: The fate of nanomaterials at biological barriers, *Biomaterials*, **174**, 41-53.

Midander K., Cronholm P., Karlsson H.L., Elihn K., Möller L., Leygraf C., Wallinder I.O., (2009), Surface characteristics, copper release, and toxicity of nano- and micrometer-sized copper and copper(ll) oxide particles: A cross-disciplinary study, *Small*, **5**, 389-399.

Morsy M.S., Aglan H.A., Abd-el-Razek M.M., (2009), Nanostructured zonolite-cementitious surface compounds for thermal insulation, *Construction and Building Materials*, **23**, 515-521.

Murugadoss S., Lison D., Godderis L., Brule S.V.D., Mast J., Brassinne F., Sebaihi N., Hoet P.H., (2017), Toxicology of silica nanoparticles: an update, *Archives of Toxicology*, **91**, 2967-3010.

Nakajima A., Miyamoto T., Sakai M., Isobe T., Matsushita S., (2014), Comparative study of the impact and sliding behavior of water droplets on two different hydrophobic silane coatings, *Applied Surface Science*, **292**, 990-996.

Nishi K., Morimoto Y., Ogami A., Murakami M., Myojo T., Oyabu T., Kadoya C., Yamamoto M., Todoroki M., Hirohashi M., Yamasaki S., Fujita K., Endo S., Uchida K., Yamamoto K., Nakanishi J., Tanaja I., (2009), Expression of cytokine-induced neutrophil chemoattractant in rat lungs by intratracheal instillation of nikel oxide nanoparticles, *Inhalation Toxicology*, **21**, 1030-1039.

Oberdörster G., Oberdörster E., Oberdörster J., (2005), Nanotoxicology: An emerging discipline evolving from studies of ultrafine particles, *Environmental Health Perspectives*, **113**, 823-839.

O'Brien N., Cummins E., (2008), Recent developments in nanotechnology and risk assessment strategies for addressing public and environmental health concerns, *Human and Ecological Risk Assessment*, **14**, 568-592.

Ogami A., Morimoto Y., Myojo T., Oyabu T., Murakami M., Nishi K., Kadoya C., Tanaka I., (2007), Histopathological changes in rat lung following intratracheal instillation of silicon carbide whiskers and potassium octatitanate whiskers, *Inhalation Toxicology*, **19**, 753-758.

Pacheco-Blandino I., Vanner R., Buzea C., (2012), *Introduction to Nanoparticle and Nanomaterial Toxicity*, In: *Toxicity of Building Materials*, Pacheco-Torgal F., Jalali S., Fucic A. (Eds.), Woodhead Publishing, Oxford Cambridge Philadelphia New Delhi, 427-475.

Pacheco-Torgal F., Jalali S., (2011), Nanotechnology: Advantages and drawbacks in the field of construction and building materials, *Construction and Building Materials*, **25**, 582-590.

Pearce J.M., (2012), Physics: Make nanotechnology research open-source, *Nature*, **491**, 519-521.

Putheti R.R., Okigbo R.N., Advanapu M.S., Chavanpatil S., (2008), Nanotechnology importance in pharmaceutical industry, *African Journal of Pure and Applied Chemistry*, **2**, 27-31.

Raki L., Beaudoin J., Alizadeh R., Makar J., Sato T., (2010), Cement and concrete nanoscience and nanotechnology, *Materials (Basel)*, **3**, 918-942.

Rana A.K., Rana S.B., Kumari A., Kiran V., (2009), Significance of Nanotechnology in Construction Engineering, *International Journal of Recent Trends in Engineering*, **1**, 6-8.

Reeves J.F., Davies S.J., Dodd N.J.F., Jha A.N., (2008), Hydroxyl radicals (*OH) are associated with titanium dioxide (TiO_2) nanoparticle-induced cytotoxicity and oxidative DNA damage in fish cells, *Mutation Research*, **640**, 113-122.

Rincón A.G., Pulgarin C., (2004a), Effect of pH, inorganic ions, organic matter and H_2O_2 on *E. coli* K12 photocatalytic inactivation by TiO_2: Implications in solar water disinfection, *Applied Catalysis B: Environmental*, **51**, 283-302.

Rincón A.G., Pulgarin C., (2004b), Bactericidal action of illuminated TiO_2 on pure *Escherichia coli* and natural bacterial consortia: Post-irradiation events in the dark and assessment of the effective disinfection time, *Applied Catalysis B: Environmental*, **49**, 99-112.

Saleh H.M., El-Sheikh S.M., Elshereafy E.E., Essa A.K., (2019), Mechanical and physical characterization of cement reinforced by iron slag and titanate nanofibers to produce advanced containment for radioactive waste, *Construction and Building Materials*, **200**, 135-145.

Saleh H.M., El-Saied F.A., Salaheldin T.A., Hezo A.A., (2018), Macro- and nanomaterials for improvement of mechanical and physical properties of cement kiln dust-based composite materials, *Journal of Cleaner Production*, **204**, 532-541.

Sanchez F., Sobolev K., (2010), Nanotechnology in concrete - A review, *Construction and Building Materials*, **24**, 2060-2071.

Sarikaya M., Tamerler C., Jen A.K.Y, Schulten K., Baneyx F., (2003), Molecular biomimetics: nanotechnology through biology, *Nature Materials*, **2**, 577-585.

SCENIHR, (2006), The appropriateness of existing methodologies to assess the potential risks associated with engineered and adventitious products of nanotechnologies, SCENIHR/002/05, On line at: https://ec.europa.eu/health/ph_risk/committees/04_scenihr/docs/scenihr_o_003b.pdf.

Schimpel C., Resch S., Flament G., Carlander D., Vaquero C., Bustero I., Falk A., (2017), A methodology on how to create a real-life relevant risk profile for a given nanomaterials, *Journal of Chemical Health & Safety*, **25**, 12-23.

Schmid K., Riediker M., (2008), Use of nanoparticles in Swiss industry: A targeted survey, *Environmental Science & Technology*, **42**, 2253-2260.

Shakeel M., Jabeen F., Shabbir S., Asghar M.S., Khan M.S., Chaudhry A.S., (2016), Toxicity of nano-titanium dioxide (TiO_2-NP) through various routes of exposure: a review, *Biological Trace Element Research*, **172**, 1-36.

Sharma N., Ojha H., Bharadwaj A.,Pathak D.P., Sharma R.K., (2015), Preparation and catalytic applications of nanomaterials: a review, *RSC Advances*, **5**, 53381-53403.

Shen S., Burton M., Jobson B., Haselbach L., (2012), Previous concrete with titanium dioxide as a photocatalyst compound for a greener urban road environment, *Construction and Building Materials*, **35**, 874-883.

Shimomura M., Sawadaishi T., (2001), Bottom-up strategy of materials fabrication: A new trend in nanotechnology of soft materials, *Current Opinion in Colloid & Interface Science*, **6**, 11-16.

Singh P., Nanda A., (2012), Nanotechnology in cosmetics: a boon or bane? *Toxicological & Environmental Chemistry*, **94**, 1467-1479.

Sobolev K., Flores I., Torres-Martinez L.M., Valdez P.L., Zarazua E., Cuellar E.L., (2009), *Engineering of SiO_2 Nanoparticles for Optimal Performance in Nano Cement-Based Materials*, In: *Nanotechnology in Construction 3*, Bittnar Z., Bartos P.J.M., Němeček J., Šmilauer V., Zeman J. (Eds.), Springer, Berlin Heidelberg, 139-148.

Spitzmiller M., Mahendra S., Damoiseaux R., (2013), *Safety Issues Relating to Nanomaterials for Construction Applications*, In: *Nanotechnology in Eco-Efficient Construction Environment*, Pacheco-Torgal F., Diamanti M.V., Nazari A., Goran-Granqvist C. (Eds.), Woodhead Publishing Limited, Oxford Cambridge Philadelphia New Delhi, 127-158.

Srivastava D., Wei C., Cho K., (2003), Nanomechanics of carbon nanotubes and composites, *Applied Mechanics Reviews*, **56**, 215-230.

Stone V., Führ M., Feindt P.H., Bouwmeester H., Linkov I., Sabella S., Murphy F., Bizer K., Tran L., Ågerstrand M., Fito C., Andersen T., Anderson D., Bergamaschi E., Cherrie J.W., Cowan S., Dalemcourt J.F., Faure M., Gabbert S., Gajewicz A., Fernandes T.F., Hristozov D., Johnston H.J., Lansdown T.C., Linder S., Marvin H.J.P., Mullins M., Purnhagen K., Puzyn T., Jimenez A.S., Scott-Fordsmand J.J., Streftaris G., van Tongeren M., Voelcker N.H., Voyiatzis G., Yannopoulos S.N., Poortvliet P.M., (2018), The essential elements of a risk governance framework for current and future nanotechnologies, *Risk Analysis*, **38**, 1321-1331.

Subramanian V., Semenzin E., Hristozov D., Zabeo A., Malsch I., McAlea E., Murphy F., Mullins M., Harmelen T.V., Ligthart T., Linkov I., Marcomini A., (2016), Sustainable nanotechnology decision support system: bridging risk management, sustainable innovation and risk governance, *Journal of Nanoparticle Research*, **18**, 1-13.

Takagi A., Hirose A., Nishimura T., Fukumori N., Ogata A., Ohashi N., Kitajima S., Kanno J., (2008), Induction of mesothelioma in p53+/- mouse by intraperitoneal application of multi-wall carbon nanotube, *The Journal of Toxicological Sciences*, **33**, 105-116.

Valsami-Jones E., Lynch I., (2015), How safe are nanomaterials? *Science*, **350**, 388-389.

Van Broekhuizen P., Van Broekhuizen F., Cornelissen R., Reijnders L., (2011), Use of nanomaterials in the European construction industry and some occupational health aspects thereof, *Journal of Nanoparticle Research*, **13**, 447-462.

Wang F., Gao F., Lan M., Yuan H., Huang Y., Liu J., (2009), oxidative stress contributes to silica nanoparticle-induced cytotoxicity in human embryo kidney cells, *Toxicology in Vitro*, **23**, 808-815.

Wang H., Chen E., Jia X., Liang L., Wang Q., (2015), Superhydrophobic coatings fabricated with polytetrafluoroethylene and SiO_2 nanoparticles by spraying process on carbon steel surfaces, *Applied Surface Science*, **349**, 724-732.

Wang X.Y., Li D.Y., (2003), Mechanical, electrochemical and tribological properties of nano-crystalline surface of 304 stainless steel, *Wear*, **255**, 836-845.

Wang Z., Zhang K., Zhao J., Liu X., Xing B., (2010), Adsorption and inhibition of butyrylcholinesterase by different engineered nanoparticles, *Chemosphere*, **79**, 86-92.

Wei W., Sethuraman A., Jin C., Monteiro-Riviere N.A., Narayan R.J., (2007), Biological properties of carbon nanotubes, *Journal of Nanoscience and Nanotechnology*, **7**, 1284-1297.

West G.H., Lippy B.E., Cooper M.R., Marsick D., Burrelli L.G., Griffin K.N., Segrave A.M., (2016), Toward responsible development and effective risk management of nano-enabled products in the US construction industry, *Journal of Nanoparticle Research*, **18**, 1-27.

Whitesides G.M., (2005), Nanoscience, nanotechnology, and chemistry, *Small*, **1**, 172-179.

Yaghoubi H., Taghavinia N., Alamdari E.K., (2010), Self-cleaning TiO_2 coating on polycarbonate: Surface treatment, photocatalytic and nanomechanical properties, *Surface and Coatings Technology*, **204**, 1562-1568.

Ye Y., Liu J., Chen M., Sun L., Lan M., (2010a), In vitro toxicity of silica nanoparticles in myocardial cells, *Environmental Toxicology and Pharmacology*, **29**, 131-137.

Ye Y., Liu J., Xu J., Sun L., Chen M., Lan M., (2010b), Nano-Sio_2 induces apoptosis via activation of p53 and Bax mediated by oxidative stress in human hepatic cell line, *Toxicology in Vitro*, **24**, 751-758.

Yokel R.A., MacPhail R.C., (2011), Engineered nanomaterials: exposures, hazards, and risk prevention, *Journal of Occupational Medicine and Toxicology*, **6**, 7-33.

Zalk D.M., Paik S.Y., Swuste P., (2009), Evaluating the Control Banding Nanotool: A qualitative risk assessment method for controlling nanoparticle exposures, *Journal of Nanoparticle Research*, **11**, 1685-1704.

Zhao J., Li N., Wang S., Zhao X., Wang J., Yan J., Ruan J., Wang H., Hong F., (2010), The mechanism of oxidative damage in the nephrotoxicity of mice caused by nano-anatase TiO_2, *Journal of Experimental Nanoscience*, **5**, 447-462.

Zhang J., Ren L., Zou Y., Zhang L., Wei J., Li Y., Wang., Sun Z., Zhou X., (2016), Silica nanoparticles induce start inhibition of meiosis and cell cycle arrest via down-regulating meiotic relevant factors, *Toxicology Research*, **5**, 1453-1464.

Zhang W., Suhr J., Koratkar N., (2006), Carbon nanotube/polycarbonate composites as multifunctional strain sensors, *Journal of Nanoscience and Nanotechnology*, **6**, 960-964.

Zhu W., Bartos P.J.M., Porro A., (2004), Application of nanotechnology in construction. Summary of a state-of-the-art report, *Materials and Structures*, **37**, 649-658.

Zweck A., Bachmann G., Luther W., Ploetz C., (2008), Nanotechnology in Germany: from forecasting to technological assessment to sustainability studies, *Journal of Cleaner Production*, **16**, 977-987.