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Emerging risk in the construction industry: Recommendations for managing exposure to nanomaterials

Beatriz María Díaz-Soler [a], María Dolores Martínez-Aires [b] & Mónica López-Alonso [c]

[a] Escuela Técnica Superior de Ingeniería de la Edificación, Universidad de Granada, Granada, España. atriz@correo.ugr.es
[b] Escuela Técnica Superior de Ingeniería de la Edificación, Universidad de Granada, Granada, España. aires@ugr.es
[c] Escuela Técnica Superior de Ingeniería de Caminos, Canales y Puertos, Universidad de Granada, Granada, España. mlopeza@ugr.es

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Abstract
Nanotechnology has aroused great interest in the construction industry because new materials with outstanding properties are being designed, and the features of traditional materials can be improved. However, exposure to nanomaterials is the most recent new emerging risk in the construction industry and the current knowledge about this topic is limited. This paper aims to identify the main aspects regarding the exposure to and use of nanomaterials in the construction sector from a risk prevention perspective. This starting point allows authors to establish a set of recommendations structured in order to identify how and where to act in order to manage the risk of exposure to nanomaterial on construction sites.

Keywords: emerging risk; safety risks; health risk; engineering controls; organizational measures; personal protection equipment.

Riesgo emergente en la industria de la construcción: Recomendaciones para controlar la exposición a nanomateriales

Resumen
La nanotecnología ha despertado un gran interés en la industria de la construcción por el diseño de nuevos materiales con propiedades extraordinarias y por la mejora de las prestaciones de los materiales tradicionales. Sin embargo, la exposición a nanomateriales es un nuevo riesgo emergente en la industria de la construcción y los conocimientos actuales sobre este tema son limitados. Este documento tiene como objetivo identificar los principales aspectos relacionados con la exposición y el uso de nanomateriales en el sector de la construcción desde la perspectiva de la prevención de riesgos. Este punto de partida permite a los autores establecer una serie de recomendaciones estructuradas para identificar cómo y dónde actuar con el fin de controlar el riesgo de exposición a los nanomateriales en las obras de construcción.

Palabras clave: riesgo emergente; riesgos para la seguridad; riesgos para la salud; medidas de control técnicas; medidas de organización; equipos de protección personal.

1. Introduction

The European Commission defines a nanomaterial as: a natural, incidental or manufactured material containing particles, in an unbound state, or as an aggregate or as an agglomerate where, for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1 nm-100 nm [1]. This is not, however, a definitive definition; in fact it should have been revised in 2014 in the light of new scientific advances. Nanostructured materials were not considered in the previous definition, but according to the International Organization for Standardization they should have been. Even though almost all materials have surfaces that are morphologically and chemically heterogeneous at the nanoscale, if they have been intentionally modified or texturized [2] they should be catalogued as an engineered nanomaterial. From the point of view of preventing risks in the workplace, it is necessary to distinguish between those produced intentionally and with specific properties (engineered or manufactured nanomaterials), and those that are made up of ultrafine particles (incidental and natural nanomaterial).

1.1. Economic and technological progress

We are possibly facing a new economic and social revolution: the nano-revolution [3] or the sixth economic wave [4]. Nanotechnology has been identified as an essential facilitating technology [5] that will be the basis for innovation. New products will bring these scientific and technological developments to the market. This boom was quantified in a macroscopic study of indicators based on nanotechnological patents [6], and this positive trend has been confirmed [7]. In fact, estimates of this economic and technological growth [8] show that the volume of revenue from nanotechnology-based products will rise to 2 billion Euros in 2015 [9].

1.2. Nanoproducts in construction

Many of the nanotechnology-based products currently used in daily life can be found in on-line inventories. They are present in almost all fields, including construction, agriculture, sports, medicine, cleaning, computers and electronics, cosmetics… [10-13]. This last area is where nanotechnology has had the biggest impact [14].

The construction industry has been considered to be of the most promising fields for nanotechnology [15], but it is still in the early stages of expansion [16]. There are several reasons for this, but generally speaking there is little knowledge of nanotechnology in the industrial sector [17], in the construction business [18] and among the general public [19].

In spite of this, the potential of nanomaterials in the construction industry cannot be ignored, particularly for nanoparticles of titanium dioxide (TiO_2), zinc oxide (ZnO), aluminium oxide (Al_2O_3), silver (Ag) and silica (SiO_2) [20]; their use is only expected to increase [21]. Many reviews and reports [17,22-30] provide a detailed overview of applications available in construction materials such as ceramics, metals, wood, stone, etc. Some examples are mentioned hereafter. Photocatalytic concrete with nanoparticles of titanium dioxide (TiO_2) has antibacterial, self-cleaning and self-decontaminating properties that, at the same time, makes it last longer and helps it keep its look throughout its useful life [31]. Glass with nanosilica gel inside offers very good thermal and acoustic insulation properties while also avoiding annoying shadows and glare [32]. Nanostructured steels manage to gain up to five times more strength than traditional solutions [33]. There is also anti-graffiti paint that is water- and oil-proof, stopping the paint from sticking and making it easier to clean afterwards [34]. Finally smart developments have been reported, such as building materials containing nano-sensors, and self-healing materials mixed with nanoparticles [35,36].

2. Occupational health and safety

Exposure to nanomaterials is becoming one of the most significant risks in the workplace [37], particularly for the construction industry [38]. Despite being at risk when exposed to nanomaterials, workers have received very little attention in scientific studies [39]. Moreover, when comparing the construction business to other sectors, fewer studies have been conducted on the risks associated with harmful substances or toxic products [40].

Besides, there are no safety specific standards to work with nanomaterials. Although current standards in force can be applied to nanomaterials, these need to be adapt [41]. Work is being undertaken to standardize parameters and methodologies as well as create the appropriate terminology and definitions [42]. However, on the whole, European political activity to date [43] has been scarce in terms of guaranteeing secure nanotechnology development. Specifically, in the area of prevention, we are still waiting for the final conclusions on Occupational Health and Safety legislation [44]; these should have been finished in 2013.

It became clear that it was necessary to delve deeper into nano-safety. Initiatives have been put forward, such as the EU Nano Safety Cluster, which aims to maximize the synergies between those research projects that are looking at nanotechnology from the point of view of toxicology, ecotoxicology, exposure assessment, interaction mechanisms, risk assessment and standardization [45]. One Nano Safety Cluster´s research project is in the area of scaffolding. It deals with strategies, methods and tools to manage risks with nanomaterials in the construction industry sector [46]; the final results have still not been published. The following papers and reports address this topic [18,20,47,48].

2.1. Exposure to nanomaterials: identification and quantification

There are many scenarios during the life-cycle of nanomaterials that are used in construction, for example nanoproduct manufacturing, construction sites or disposal in the demolition field [47]. This paper focuses on construction sites.

On construction sites, the riskiest tasks involve handling dusty or liquid materials or when their application generates dust or aerosols, for example when spraying a nano-coating, or during cleaning activities. Conversely, risks of exposure to nanoparticles when handling solid prefab-nanoproducts, nano-enhanced ceramics for example, are expected to be small because the nanomaterials are embedded in a matrix; however, exposure may take place as the material wears [18].

In order to control workers' exposure to nanomaterials, industrial hygiene cannot continue without changes [49]. In fact, the usual exposure index [mass per unit of volume] is not the most appropriate because it does not take into account other crucial toxicity parameters when particles become very small [50]. Besides, the instruments, techniques and traditional measurements of aerosol sampling are not the best solution to assess exposure to a nanostructured particle aerosol [51,52]; although, work is being done to resolve these issues [53]. Moreover, it is necessary to understand the relationship between the nanomaterial parameters and their toxicological effects; however, for the time being, there is no international consensus [54]. However, there are proposals such as the nano reference values (NRV) [55] and environmental limit values, which are based on known values for the parent materials and distinguish between insoluble and soluble for derivatives of mutagenic, carcinogenic compounds, or any that alter the reproductive function of fibrous nanomaterials [56]. In addition, there are also exposure values for nanoparticles of titanium dioxide (TiO_2) [57] and for carbon nanotubes [58-60].

There are few case studies on environmental exposure that apply building nanoproducts. Their results indicate that certain levels of exposure are acceptable; for example, analysis of exposure when spraying self-cleaning coatings with nanoparticles of titanium dioxide (TiO_2). Also, three cases that deal with mortar repair using nanoparticles of silica (SiO_2) conclude that exposure was below the reference values [61,62], and it even suggested that this exposure might be lower as the nanoparticles detected may originate from the electrical equipment and the machinery used [20]. Another study evaluates exposure when making mortars with nanoparticles of zirconium dioxide (ZrO_2). It concludes that the occupational limit values were not reached, but they were greater than the values for indoor air [63].

2.2. Damage to health: toxicokinetic and health effects

The deposit and absorption of nanoparticles in the organism occurs through three main paths: by inhalation, through the skin and by digestive tract [64]. In construction workers it occurs mainly by inhalation [38]. Depending on the particles' size, shape and chemical composition, they are capable of entering the lungs and can reach the different parts of the respiratory system [65], see Figure 1.

The nanoparticles can also enter the organism through the skin [66] and by ingestion as a result of poor safety practices, as well as by swallowing materials trapped in the upper respiratory tract [67]. In relation to transport of nanomaterials through the organism, it is also necessary to consider translocation, which is a specific property of nanomaterials. Nanomaterials can cross biological barriers unaltered and appear in various other parts of the body [68]. Finally, removal processes through the body may either be entirely or partially by chemical or physical elimination [69].

Factors that influence nanoparticle toxicity depend on exposure, the organism and the nanomaterials [69]. Recent reviews summarize the results of studies that suggest nanomaterials are harmful to our health [70-73]. For example, an in vivo study concluded that of titanium dioxide (TiO_2) nanoparticles seem to induce DNA damage and genetic instability [74]. Alternatively, other in vivo studies looking at entry through the skin with different formulations concluded that negative effects on health were not expected [75]. Another example, carbon nanotubes could have an even greater capacity to cause mesotheliomas than crocidolite asbestos [76], although these findings were questioned because nanotubes are not absorbed

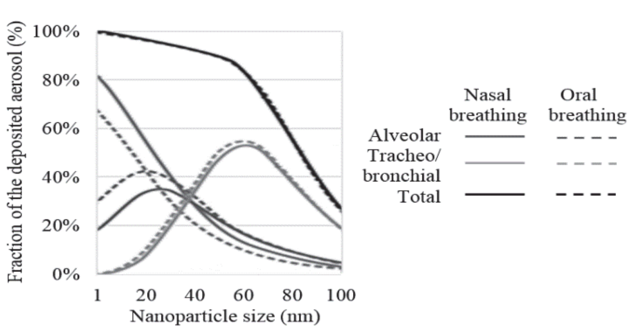

Figure 1. Total and regional deposit of nanoparticles depending on the particle diameter.
Source: Adapted from [65].

through the lungs [77]. This shows that the current knowledge is limited and sometimes contradictory regarding the toxicology of nanomaterials.

2.3. Impact on safety: risk of fire and explosion

In general, the catalytic effects and the risk of fire or explosion should be taken into account in the safety assessment when handling nanopowder [78]. However, it is also thought that the specific environmental conditions needed to pose a risk are not easily obtained [67]. In any case, it is important to consider other factors that increase the probability of ignition and the violence of the explosion such as the presence of a solvent, humidity, temperature, etc. [79,80]. In fact, these factors are important in different jobs on construction sites; they could indeed be present simultaneously and incompatibilities are possible [48].

3. Recommendation for managing exposure to nanomaterials

Faced with the difficult task of carrying out a quantitative risk assessment owing to the absence of firm toxicological and exposure information, qualitative risk assessment, control banding (CB) allows a simplified process to be used in order to determine the potential risk of exposure probability and severity of damage, as well as the corresponding risk level and their associated safety measures: general ventilation (level 1), ventilation by localized extraction or smoke hoods (level 2), confinement (level 3) and seeking external advice (level 4) [81]. Also, there are other methodologies and strategies for risk assessments, for example, taking into account the exposure route of entry, the aspect of identification and the toxicological screening; these three levels are defined with their corresponding actions [82].

In this paper a set of preventive and protective measures is presented according to the characteristics of the nanomaterial: in suspension (dispersed nanomaterials aerosol), solid form freely mobile nanomaterials (dispersed nanomaterials dust and friable solids) and fixed in a solid matrix or embedded on a surface [83]. The principal aim is to avoid entry into the body by inhalation or through the skin (and thus by ingestion). The authors choose this strategy, because the characteristics of nanomaterials determine the exposure risks [84]. In fact, it is important to note that some building nanoproducts may display different material forms during their life-cycles, and this affects potential occupational exposure. For example, this aspect is included in the Risk Assessment Document and the case of Sepiolite Clay is analyzed [85].

The recommendations presented are the result of a review of scientific literature and documentation from prestigious Institutes of Occupational Safety and Health. The vast majority of safety guidelines and protocols to manage exposure to nanomaterials, focus on laboratory research environments. Only some specific interactive examples for construction sites that have been provided by BAuA (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin) [86]. Prevention criteria and measures protection oriented research in general and construction environments have been unified

Table 1.
Elimination of nanoproducts.

Characteristics of nanoproduct	Action	Recommendations
When the use of nanoproducts arises	Elimination.	If possible, it should only be considered if the specific properties of nanomaterials offset possible new risks [41].

Source: Own elaboration.

Table 2.
Substitution of nanoproduct, working equipment and working processes.

Characteristics of nanoproduct	Action	Recommendations
Solid form freely mobile nanomaterials.	Nanoproduct replaced.	The option that generates the least dust during use is always recommended. This is critical in the case of nanopowders where the option that generates the least dust during use is always recommended, for example with cement [86].
	Working equipment replaced.	Suction systems to trap dust on grinding and cutting equipment are always recommended [86]. These systems should have filters HEPA (High Efficiency Particulate Air) [67].
In suspension.	Working processes replaced.	Using other equipment that does not generate aerosols, for example for the application of paints use rollers instead of sprays.

Source: Own elaboration

Table 3.
Engineering controls.

Characteristics of nanoproduct	Action	Recommendations
Solid form freely mobile Nanomaterials & in suspension	Localized extraction.	When confinement is not possible, it local exhaust will be used [88]. Using laboratory chemical hoods on the construction site is impossible; therefore, using blower/vacuum electric portable is proposed as alternative. Ventilation by dilution can control the level of environmental pollution of nanoparticles [67]. Ventilation by dilution cannot, in any case, be a single measure of exposure control [88]. Ventilation by dilution should be complementary to the application of localized extraction or confinement. It is not recommended as a single measure, as contaminant dispersion to other areas could be aided.
Solid form freely mobile nanomaterials: only friable solids	Confinement.	The works should be carried out in closed circuit systems [41]. Use glove-bags [88]. Carrying out the tasks in a closed circuit system is impossible. However, it is possible to use glove-bags to handle small friable solids.

Source: Own elaboration.

Table 4.
Work practices.

Characteristics of nanoproduct	Action	Recommendations
Solid form freely mobile nanomaterials.		Take into account the operating temperature of the electrical equipment [78].
Solid form freely mobile nanomaterials & in suspension.	Work practices related To environment (equipment and work processes).	Place nonskid mats on the floor so that any material that falls on the mats can be easily cleaned by just removing them. Another advantage is that the material is not dragged elsewhere [89]. People should not move near the worker handling the nanoproducts to avoid air turbulence [90]. Section off the work area [69]. Use one of the several proposed pictograms, because for the time being there is no standard European pictogram to warn of danger from exposure to nanomaterials.
Solid form freely mobile nanomaterials & in suspension & fixed in a solid matrix or embedded on a surface.	Personal hygiene measures.	Do not store or consume food and drink in the workplace, avoid applying cosmetics, wash hands before eating or leaving the job and avoid touching your face or other exposed parts of the body with contaminated fingers [67].
	Treatment nanowastes	Nanowaste should be treated as hazardous waste [91]. Safe practices should be extended to treat nanowastes [92].
	Work practices related to PPE.	Storing clothes and protective gear with loose contamination in a closed bag or other sealable container [93]. Pay attention to possible wear of personal protection measures [94] Close attention must be paid that gloves and cuffs fit correctly [89].
In the event of solid-spills.	Spills Control.	Wet systems and vacuum cleaners equipped with HEPA filters should always be used [67].
In the event of liquid-spills.		Adsorbents should be used [67].

Source: Own elaboration.

Table 5.
Personal Protection.

Characteristics of nanoproduct	Action	Recommendations
Solid form freely mobile nanomaterials & in suspension & fixed in a solid matrix or embedded on a surface.	Gloves	Nitrile gloves are generally recommended but latex is also used [89]. However, if it is necessary to protect against others risks, the gloves will be suitable.
	Coveralls	Coverall nonwoven: Tyvek-type [89].
Solid form freely mobile nanomaterials & in suspension.	Respiratory protection	FF P3-type disposable masks have been recommended [89]. FF P2-type disposable masks have been recommended [86]. In this case, we recommend FF P3-type, for greater worker´s protection.
	Eye protection	As a minimum, close fitting safety glasses should be worn [95].

Source: Own elaboration.

and selected to be applied to construction sites. These basic key recommendations for exposure to nanomaterials in the construction workplace are described below, following the stages of the traditional Industrial Hygiene structure from a conservative and preventive outlook [87]. It is important to note that these recommendations should be in line with other risks detailed on construction sites: falls from heights, electrocution, etc.

In the tables below, the characteristics of the nanoproducts, the action and recommendations that should be taken account is presented. Table 1 presents the eliminations as the first option, despite it being the most complicated. Table 2, presents the different types of replacements for products, working equipment and processes. In this case we should take into account the risks posed by the new replacement, so the choice influences the safety conditions. The engineering controls are summarized in Table 3. In Table 4, work practice suitability is listed and finally, Table 5 shows personal protection at work using nanoproducts

Complementarily to all the above steps, workers should receive information and training and should be consulted on the planning, organization and implications for health and safety on the use of nanotechnology [96].

Regarding health surveillance, although it is not mandatory and there is no evidence of the impact of nanomaterials based on epidemiological studies [48], the current knowledge is sufficient to carry out specific protocols [97]; for example, CSIC (Centro Superior de Investigaciones Científicas) have already developed specific medical protocols in Spain [98].

4. Conclusions

The nanotechnology has a substantial impact in the construction industry. The landscape of occupational risk prevention when using nanomaterials is vague and complicated. Thus, it is necessary to conduct more research focusing on this topic in order to suitably safeguard workers.

Previous experience with hazardous materials, such as asbestos, should be used to set a precedent and move forward cautiously [48]. With this principle of precaution in mind, the most important contribution made by this work has been to identify a series of specific recommendations according to the characteristics of the nanomaterial and from a conservative point of view to manage exposure to nanomaterial in workplace construction. These recommendations should keep up with new scientific breakthroughs.

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B.M. Díaz-Soler, received her BSc in Technical Architecture in 2011 and her MSc. in Management and Integrated Safety in Construction in 2013, all them from the Universidad of Granada, Spain. At present, she is a PhD student on the Doctoral programme in Civil Engineering at the University of Granada. Her research interests include Health and Safety, Nanotechnology in Construction Industry and waste management.
ORCID: orcid.org/0000-0003-4332-1456

M.D. Martínez-Aires, received her BSc. in Organization Industrial Engineering 2004 from the University of Jaén, Spain, and Technical Architecture in 1993, from the University of Granada, Spain. She received her PhD in Civil Engineering in 2009 from the University of Granada, Spain. Currently, she is a full professor in the Department of Building Construction at the University of Granada. Her research interests include: Health and Safety, Prevention through Design (PtD), Ergonomics and Bibliometric Analyses.
ORCID: orcid.org/0000-0002-9292-5048

M. López-Alonso, received her BSc. in Civil Engineering in 1995 from the University of Granada, Spain. She received her PhD degree in Civil Engineering in 2013 from the University of Granada, Spain. Currently, she is an associate professor in the Department of Construction Engineering and Projects at the University of Granada. Her research interests include: Health and Safety, Prevention costs, Ergonomics, Construction Materials and Bibliometric Analyses.
ORCID: orcid.org/0000-0002-1343-1374