NANOMATERIALS IN THE CONSTRUCTION INDUSTRY

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Abstract

Nanotechnology and the nanomaterials industry has created a promising new type of materials. The nanomaterials have different physical and chemical properties, in comparison to their original materials, potentiating great improvements in the products of the various industries. The main objective of this dissertation is to synthesize the current knowledge about the presence of nanomaterials in the construction industry. Initially, a contextualization of the world of nanotechnology and nanomaterials is presented, followed by a presentation of the most promising nanomaterials in the construction industry, particularly in the area of energy efficiency and coatings, and other building materials, such as concrete, steel and wood. The dissertation also includes a brief presentation on the evolution of the commercialization of nanomaterials, and the health risks that these new materials can create. It can be concluded that the nanomaterials industry is still a recent, small and developing industry. It's an industry that is expected to grow over the next few years and become more solid.

Keywords: Nanomaterials; Construction Industry; Applications; Commercialization Evolution; Health risks.

1 Introduction

At the present technological evolution is constant. Every day new discoveries are made in the most diverse domains and the most diverse equipment and processes are invented, that not only enable new technological advances, but also improve product quality.

The construction sector, compared to others, in particular the electronics, is currently seen by society as being little innovative. It's a very competitive sector, which is often driven by the lowest price criterion.

The innovation and development of new products and solutions involves large investments, not only during the research and technological development process, but also during the implementation and commercialization of the new solution. The competitive nature of the construction sector coupled with the high costs of some innovative solutions often leads to the use of traditional solutions, as there is no predisposition to increase the cost of the project.

On the other hand, we can say that there is a growing concern with the quality of products. Studies on the construction lifecycle costs have shown that the solution associated with lower initial investments does not always represent the most economically viable solution (Real, 2010). It's therefore concluded that making higher investments in the initial stages of construction will be beneficial to achieve a better quality solution and potentially reduce the total costs over the life cycle of the construction.

The nanomaterials in the construction sector, despite representing an increase in the costs of the solutions, have a role on improving the properties of the materials used in buildings, enhancing their quality

This dissertation aims to synthesize the existing knowledge in the field of nanomaterials in the construction industry, by conducting an analysis of the main fields of application, and identifying the nanomaterials that are already in use, and those that are in development and are expect to appear in the future in the market.

It’s also sought to know the evolution of the commercialization of nanomaterials and how they are presented by manufacturers, and analyze the available information on the potential impact of nanomaterials on health and environment throughout their life cycle.

2 Nanotechnology and Nanomaterials

The concept of nanotechnology was originally presented by the American physicist Richard Feynman in 1959 in his lecture titled "There's Plenty of Room at the Bottom" at the meeting of the North American Physics Society at CalTech, where he suggested that there is a field of physics still to be studied, and therefore a new world of possibilities at the molecular level, (Pacheco-Torgal & Jalali, 2011).

Nanotechnology can be defined, in general, as the manipulation of matter at the nanometer scale, that is, at the nanoparticle level. A nanoparticle is characterized by having at least one of its dimensions between 1 and 100 nanometers ($1nm = 10^{-9}m$). As comparison, and to be more noticeable the size of the nanometric scale, it is noted that the human hair has a thickness of 80,000 nm and that the double helix of the human DNA has a diameter of 2 nm, (Pacheco-Torgal & Jalali, 2011).

According to the recommendations for the European Commission's definition of nanomaterial (European Commission, 2017), a material can be generally defined as a nanomaterial if it consists of nanoparticles in more than 50% of their constitution. It should be noted, however, that when a nanomaterial is in the form of particles, they may be presented as isolated particles, as agglomerates, joined by weak forces such as van der Waals, or as aggregates, joined by strong forces such as covalent, (European Commission, 2017; Bouwmeester, Byrne, Casey, & Chambers, 2011). The different forms of presentation of nanomaterials in the form of particles defines a need for a careful characterization of this type of materials in order to obtain a correct classification.

2.1 Characterization and properties of nanomaterials

The different forms of presentation of nanomaterials in the form of particles requires a careful characterization not only of the particles that are in their isolated state but also of those that are agglomerated or aggregated. The achievement of this characterization is fundamental to exploit the potential of nanomaterials and optimize the characteristics of the products that contain them, (NBCI, 2017). When analyzing nanoparticles, the characteristics that are sought are the following: Particle size and shape; Superficial features, such as specific surface area; Chemical composition and charge;

Others, such as their solubility, UV radiation stability and thermal stability, (NBCI, 2017; Bouwmeester et al, 2011).

To obtain these characteristics there is no specific method that is considered the most appropriate. The choice of the method is based on the constraints of the type of sample, desired information, and cost of the method. Several techniques and methods are currently being used to characterize nanoparticles. It turn out that applying different techniques to a unique sample leads to significant differences in results as well as different levels of precision.

While the materials generally have constant properties regardless of their size, in the field of nanomaterials it's generally the size of particles that dictates the physical and chemical properties. This phenomenon begins to manifest itself when the percentage of atoms on the surface of the material becomes relevant against the percentage of atoms that are in its interior, that is, when it approaches the scale of the nanometer. It's concluded that nanoparticles are distinguished by their large specific surface area that will dictate their physical and chemical properties (News Medical Life Siences, 2017). The optical properties, the melting point, the mechanical resistance, and the electrical and chemical properties are some of the properties influenced by the size of the nanoparticles, thus justifying the need for a careful characterization of these materials.

2.2 Production and Classification of nanomaterials

The influence that the particle size has on the properties of the nanomaterials requires a controlled production in order to obtain the desired dimensions, structures and properties. There are several ways of producing nanomaterials, the most commons are top-down and bottom-up strategies, (Raab, Simkó, Fiedeler, Nentwich, & Gazsó, 2011).

The top-down strategy consists of reducing the particle size of the material through suitable milling processes, which may be purely physical and abrasive or may employ chemical reactions to accelerate and facilitate the milling process. In comparison to the bottom-up strategy, the top-down strategy does not guarantee complete control of the shape and size of the final particles. In the top-down strategy there is also the risk of contamination of the product by abrasion of the milling agents. The bottom-up strategy, on the other hand, consists of obtaining molecular structures through chemical processes. Due to its nature, the bottom-up strategy, allows the control of the sizes and shapes of the desired structures.

Concerning the nanomaterials classification, these can be divided according to their composition into: Materials based on carbon, Metal-based materials, Dendrimers and Composites.

The carbon-based materials are constituted by carbon and may be presented for instance in the form of spheres (fullerenes), or in the form of tubes (nanotubes). The materials based on metals are obtained from metals, and they include the quantum dots, the gold and silver nanoparticles, and metallic oxides such as titanium dioxide. The dendrimers are nanometric structures of polymers that develop through a tree like structure in several branches from a central point. The composites combine different types of nanoparticles, or nanoparticles and materials of higher dimensions, and may have an internal nanostructure or only a surface nanostructure, (AZoNano, 2017).

Regarding form, nanomaterials can be distinguished from each other by the number of dimensions that they present at the nanometer scale. Nanomaterials can exhibit one, two or three of their dimensions in the nanometer scale, resembling a thin film, a fiber or a particle, respectively, (Santos, 2013).

3 Nanomaterials in the construction industry

Currently, despite the vast possibilities and applications of nanomaterials in the construction industry, there's still no large-scale demand and use of nanomaterials. This low demand comes mainly from the high cost of these materials compared to the ones of most frequent use. However, it is expected that there will be an increase in the use of nanomaterials in the construction due to the growing concern with the quality of the constructions and consequent demand for more efficient and durable materials. This chapter presents the most promising nanomaterials in the construction industry, in particular in the field of concrete, steel, wood, and energy efficiency and coatings.

3.1 Concrete

Concrete is one of the materials most used in the construction industry, not only for its versatility as well as for its relatively low cost. Over time, several studies have been carried out on concrete and its behavior, and it's now possible to state that its main mechanisms of degradation and their causes are known.

The nanomaterials with applications in the field of concrete are diverse. In this field of application, it's generally found that they contribute to the development of a greater mechanical resistance, and a refinement of the porosity through the reduction of the larger pores and the consequent increase of micro and nano pores. It's also observed, in general, an acceleration of the hydration reactions and the reduction of the setting time. It's also verified that the greater the incorporation of the nanomaterial, the greater the agglomeration potential, thus reducing its beneficial effects on the properties of concrete. This agglomeration can, and should wherever possible, be circumvented by the use of suitable dispersion methods during the production of concrete, in order to achieve the expected results.

In this context, it's also verified that most of the nanomaterials present in the consulted literature are in the research phase, and only a few already had practical applicability of greater relevance, namely nanosilica and titanium dioxide. A summary of the most relevant applications and properties of the nanomaterials present in the consulted literature during the execution of this subchapter is presented in Table 3.1.

Table 3-1 - Summary table of the nanomaterials used in concrete.

Nanomaterial	Shape	Applications / Influenced Properties
Nanosilica (SiO_2)	NP	↑ Mechanical Resistance ↑ Elasticity Modulus ↓ Porosity and Permeability ↑ Hydration Speed ↓ Workability Regenerative Concrete Production

Nanomaterial	Shape	Applications / Influenced Properties
Titanium Dioxide (TiO_2)	NP	↑ Mechanical Resistance ↓ Porosity and Permeability ↑ Hydration Speed ↓ Workability ↑ Abrasion, Fire and Freeze /Thaw Resistance ↓ Chlorides Penetration ↑ Chemical Retraction Self-cleaning and Air Purification Capabilities
Hematite (Fe_2O_3)	NP	↑ Mechanical Resistance ↓ Porosity and Permeability ↑ Hydration Speed Self-Monitoring Capabilities Heavy Concrete Production
Carbon Nanotubes (CNT)	NT	↑ Mechanical Resistance ↓ Porosity and Permeability ↑ Young's Module Self-Monitoring Capabilities
Graphene Oxide	TF	↑ Mechanical Resistance ↓ Porosity and Permeability ↑ Hydration Speed ↓ Workability
Nano Clays	NP	↑ Mechanical Resistance ↓ Porosity and Permeability ↑ Hydration Speed ↓ Workability
Calcium Carbonate ($CaCO_3$)	NP	↑ Mechanical Resistance ↓ Porosity and Permeability ↑ Hydration Speed ↓ Workability ↓ Chlorides Penetration
Alumina (Al_2O_3)	NP	↑ Mechanical Resistance ↓ Porosity and Permeability ↑ Hydration Speed ↓ Workability ↑ Freeze /Thaw Resistance
Chromium III Oxide (Cr_2O_3)	NP	↑ Mechanical Resistance
Legend:	**NP:** **NF:** **NT:** **TF:**	Nanoparticle Nanofiber Nanotube Thin Film

3.2 Steel

Steel, like concrete, is one of the most used materials in the construction industry, as more than a quarter of the world's annual steel production is used in building construction (Moynihan & Allwood, 2014). The domain of nanomaterials application in steel, although not as extensive as the one found in concrete, has a large list of nanomaterials, table 3.2. In this field, nanomaterials have been studied with the aim of increasing the mechanical strength, corrosion resistance, and thermal stability of steel.

A summary of the most relevant applications and properties of the nanomaterials present in the consulted literature during the execution of this subchapter is presented in Table 3.2.

Table 3-2 - Summary table of the nanomaterials used in concrete.

Nanomaterial	Shape	Applications / Influenced Properties
Chromium (Cr)	NP	↑ Mechanical Resistance ↑ Corrosion Resistance
Aluminum (Al)	NP	↑ Mechanical Resistance
Molybdenum (Mo)	NP	↑ Mechanical Resistance
Tungsten (W)	NP	↑ Mechanical Resistance
Vanadium (V)	NP	↑ Mechanical Resistance
Niobium (Nb)	NP	↑ Mechanical Resistance
Titanium Dioxide (TiO_2)	NP	↑ Durability ↑ Surface Quality
Zirconium (Zr)	NP	↑ Thermal Stability
Yttrium Oxide (Y_2O_3)	NP	↑ Thermal Stability
Legend:	**NP:** **NF:** **NT:** **TF:**	Nanoparticle Nanofiber Nanotube Thin Film

3.3 Wood

Wood has been widely used in construction as a structural and covering material. It's a lightweight, versatile, abundant and mechanically resistant material. In this context, the nanomaterials reveal the potential to promote and improve the properties of wood protection solutions, extending the useful life of wood against the action of fungi, termites, UV radiation, scratches and abrasions, improving also its fire and hygroscopicity resistance, and its mechanical properties, (Terzi, Kartal, Yilgor, Rautkari, & Yoshimura, 2016).

A summary of the most relevant applications and properties of the nanomaterials present in the consulted literature during the execution of this subchapter is presented in Table 3.3.

Table 3-3 - Summary table of the nanomaterials used in concrete.

Nanomaterial	Shape	Applications / Influenced Properties
Zinc Oxide (ZnO)	NP	↑ Prevention of Fungi, Mold and Termites ↑ Wear Resistance and Water Repellency
Silver (Ag)	NP	↑ Antimicrobial Efficacy
CNC	NP	↑ Water Repellency and Surface Proprieties
Boron Trioxide (B_2O_3)	NP	↑ Prevention of Fungi, Mold and Termites ↑ Wear Resistance and Water Repellency
Copper Oxide (CuO)	NP	↑ Prevention of Fungi, Mold and Termites ↑ Wear Resistance and Water Repellency
Cerium Oxide (CeO_2)	NP	↑ Prevention of Fungi, Mold and Termites ↑ Wear Resistance and Water Repellency
Titanium Dioxide (TiO_2)	NP	↑ Prevention of Fungi, Mold and Termites ↑ Wear Resistance and Water Repellency

Nanomaterial	Shape	Applications / Influenced Properties
Tin Dioxide (SnO_2)	NP	↑ Prevention of Fungi, Mold and Termites ↑ Wear Resistance and Water Repellency
Legend:	**NP:** **NF:** **NT:** **TF:**	Nanoparticle Nanofiber Nanotube Thin Film

3.4 Coatings and energy efficiency

The coating and finishing materials of constructions have several functions besides the decorative, in which nanomaterials can act as enhancers of its performance and durability. In this context the presence of nanomaterials in materials with coating and finishing functions of the constructions is studied, as well as their contribution to increase the energy efficiency of the constructions, namely their presence in paints, glass, insulation materials and solar panels.

A summary of the most relevant applications and properties of the nanomaterials present in the consulted literature during the execution of this subchapter is presented in Table 3.4.

Table 3-4 - Summary table of nanomaterials used for coatings and energy efficiency.

Nanomaterial	Shape	Applications / Influenced Properties
Titanium Dioxide (TiO_2)	NP	DSSC Production – Solar Panels Self-cleaning and Air Purification – Paints, Glass
Zinc Oxide (ZnO)	NP	↑ Antimicrobial Properties – Paints
Aluminum Phosphate (AlPO4)	NP	↑ Anticorrosive Properties – Paints
ATO	NP	↑ Energy Efficiency – Glass
Iron III Oxide (Fe_3O_4)	NP	↑ Energy Efficiency – Glass
Tungsten Trioxide (WO_3)	NP	Hydrophilic Surfaces – Glass
Copper (Cu)	NP	↑ PCM Conductivity – Thermal Insulation Materials
Carbon Nanofibers (CNF)	NF	↑ PCM Conductivity – Thermal Insulation Materials
Carbon Nanotubes (CNT)	NT	↑ PCM Conductivity – Thermal Insulation Materials ARCs Production – Solar Panels
Silica (SiO_2)	NP	Aerogels Production – Thermal Insulation Materials ARCs Production – Solar Panels
Legend:	**NP:** **NF:** **NT:** **TF:**	Nanoparticle Nanofiber Nanotube Thin film

4 Evolution of the commercialization

The profitability of the solutions used in the construction industry is extremely important, because without it, the new solutions will hardly be industrialized. The introduction of nanomaterials into conventional solutions or the creation of new solutions will inevitably increase the cost of these solutions, initially causing a barrier to their diffusion in the construction sector.

Despite the difficulties of introducing new products on the market, the nanomaterials industry is clearly growing. This growth can be seen in databases such as the CPI (Nanotechnology Consumer Products Inventory, 2017) and The Nanodatabase (The Nanodatabase, 2017).

Currently, through a search in the CPI, it’s verified that at the time of this dissertation are inventoried 1827 products, produced by 715 companies in 33 countries. Silver is identified as the most common nanomaterial in the products inventoried in 2015, accounting for 24% of total registered products. However, this value may not be correct, since 49% of the inventoried products to date did not present information on the used nanomaterial (Vance, et al., 2015). Regarding the specific case of the construction industry, it can be verified that are currently registered in the category of "Construction Materials" and "Paints", 87 and 22 products, respectively (Nanotechnology Consumer Products Inventory, 2017).

In the The Nanodatabase there are currently 3005 products registered, mainly produced in the USA (982 products), Germany (503 products), United Kingdom (391 products), and Denmark (128 products). Like the CPI database, this database identifies 1918 products whose nanomaterial is unknown (64% of the total identified products). In this database, the most widely known nanomaterial in the inventoried products is silver (379 products), followed by titanium (145 products) and titanium dioxide (123 products). Regarding the use of nanomaterials in the construction industry, this database identifies 40 products in the category of "Building Materials" and 36 products in the "Paints" category, (The Nanodatabase, 2017).

From the different values presented by the two databases, it can be concluded that the nanomaterials market is still an early market in which about 50% of inventoried products do not contain information about the nanoparticles used in their constitution, a danger and uncertainty for health and the environment.

5 Health risks

With the growth of the nanomaterials industry, and with the increase of the use of this type of materials, it’s possible that the human contact with the nanoparticles that constitute them start to grow. This exposure and contact with nanoparticles has raised concerns about human health and safety, and the consequences of the interaction of the human organism with this type of particles are still unknown.

The Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) has been studying the risks of nanomaterials and the extent to which they can be addressed by risk assessment measures in the European Union. The conclusion is that even though nanomaterials do not pose a danger, due to the uncertainty and lack of knowledge that still exists on this subject, the safety assessment should be done on a case-by-case basis (European Commission, 2017).

From the health point of view, nanomaterials raise concerns due to their distinct properties and unique size (Louro, Borges & Silva, 2013). For the specific case of the construction industry, nanomaterials can be released into the environment, and potentiate a risk to human health during the construction, the use and the demolition of the building. It's however during the application phases of the nanomaterial in construction and demolition of the building, where the risks are higher, due to the high volume of particles present in the air in these phases.

In the The Nanodatabase it is also possible to visualize the degree of danger to human health and environment of the various inventoried products. For the specific case of the construction industry, this database reveals that most of the inventoried products indicate a degree of danger still unknown, emphasizing the great uncertainty of this domain, (The Nanodatabase, 2017).

Based on the high uncertainty of this area, the lack of knowledge about some nanoparticles, and the fact that nanomaterials are increasingly available, it is concluded that the best way to circumvent the risks and dangers of nanomaterials to human health and environment will be through prevention.

For greater safety, contractors and construction companies should seek to minimize the diversity of nanomaterials used in the work field, because it's easier and safer to take preventive and protective measures for a single nanomaterial, used for a variety of purposes, rather than a different nanomaterial for each of the situations, (Spitzmiller, Mahendra, & Damoiseaux, 2013).

6 Final considerations

The present dissertation analyzed the main applications of nanomaterials, the evolution of their commercialization and the health risks inherent to the use of nanomaterials with relevance to the construction industry. The diversity of nanomaterials and their applications are vast, and for the same application there is the possibility of using various nanomaterials and obtaining similar or completely different results.

The literature showed that one of the areas of investigation and application of the nanomaterials with greater relevance in the construction industry is the concrete industry. In this field, the studies carried out with the incorporation of nanomaterials in concrete formulation have revealed that these can contribute to increase the mechanical resistance, reduce the setting time, reduce the porosity and change the porous space of concrete, usually associated with the reduction of their workability.

In the steel industry the applicability of nanomaterials was found to obtain a higher mechanical resistance, and greater corrosion resistance and thermal stability.

Regarding the applications of nanomaterials in wood, the study showed its capacity to increase the performance of preserving products, extending and improving the resistance and useful life of the wood against fungi, termites, UV radiation, scratches and abrasions, improving also its fire and hygroscopicity resistance, and its mechanical properties.

The study also showed interest in the application of nanomaterials in coatings and products that contribute to a higher energy efficiency of buildings, particularly their application in paints, glass, insulation materials and solar panels. The nanomaterials provide paints with self-cleaning, air-purifying, and anticorrosive properties. In glass and insulation materials, the main focus of nanomaterials is to increase their thermal performance. In solar panels, nanomaterials can contribute to increase the performance of photovoltaic cells and to obtain more sustainable buildings.

The nanomaterials industry is still a recent, small-scale and developing industry. It is an industry that is expected to grow over the next few years and become a more solid industry. One of the most highlighted concerns in the consulted literature throughout the dissertation is the fact that many of the products on the market do not present information about the nanoparticles used, confirming the recent nature of this industry and market. This lack of information on the nanoparticles used in products available on the market contributes to greater uncertainty and risk to human health and environment.

Nanomaterials alone do not pose a health risk, but its needed research and regulation on these new materials to prevent future damages. Throughout the text it was verified that the nanoparticles will be released from the nanomaterials throughout their life, reason why the consulted literature emphasize that the best way to avoid the still unknown risks inherent to these materials will be through the prevention and careful handling of the nanomaterials.

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