NANOTECHNOLOGY IN CONSTRUCTION: TOWARDS STRUCTURAL APPLICATIONS

EXTENDED ABSTRACT

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1. Introduction

The speech of the physicist Richard Feynman, entitled “There’s plenty of room at the bottom”, that took place in 1959, in a Meeting of the American Physical Society is considered the beginning of the nanotechnology era (Feynman, 1959). Nowadays, nanotechnology is a major vector of technological development. Its impact on Society has been compared to electric power at the beginning of the XIX century. Nanotechnologies have changed the perspectives, expectations and abilities to manipulate the material world. Several sets of technological areas and industrial activities were affected, from chemistry to physics, medicine to biology, electronics to mechanics, and sports to food industry.

In addition to these areas, the construction industry has also to be considered since the application of nanotechnology to some components and processes of construction is now increasing. Nanotechnology came up as a great opportunity for development, due to the original physical, chemical and thermal characteristics of nanomaterials (NMs) primarily caused by the nano-quantum dimensional surface effects. Currently, there are diverse applications of nanotechnology in the construction industry. According to the author’s knowledge (Zhu et al., 2004; Hanus and Harris, 2013; Observatory Nano, 2009) the ones that stand out the most in terms of structural applications concerns three main sub-areas of this industry: cementitious materials (cement and concrete); polymers nanocomposites; ceramic nanocomposites. Many potential applications of nanotechnology are recognized in these areas:

- Improve the primary properties of traditional construction materials (e.g. concrete);
- Add new functionalities to existing materials, e.g. self-cleaning, antimicrobial and pollution reducing properties for paints, coatings or glass;
- Create new materials, such as silica aerogels that fill an existing need for thinner, translucent and yet effective insulation, or nanoencapsulated corrosion inhibitors to fight steel corrosion;
- Produce self-sensing structures, allowing bridges and buildings to sense their own cracks, corrosion and stresses.

Beyond all the potential of the use of nanomaterials, there have also been some critical barriers to overcome in order to increase their market dissemination, namely the costs of new processing technologies and materials and the consumer skepticism to the introduction of such high-performance materials.

Taking into account all the positive and negative considerations of the application of nanotechnology in the construction industry, this study developed a detailed process of search and information treatment in order to organize the present knowledge in the research community, focusing the three main sub-areas proposed. In addition, the main applications of nanotechnology in each topic were presented, with emphasis on those with impact in the structural behavior of existing and new structures.

2. Global knowledge and market distribution

The nanotechnology revolution experienced in the last few years had a huge impact on various science fields (chemistry, engineering, biology), also affecting the construction industry. Conceptually, nanotechnology may be defined as the ability to create new structures at the smallest scale, using tools and techniques that allow the understanding and manipulation of matter at nanoscale, generally from 0.1 to 100 nm (Zhu et al., 2004). In this sense, nanotechnology currently covers nanomaterials, such as nanoparticles (NPs), nanotubes, nanostructured materials and nanocomposites, nanotools (tools and
scanning probe microscopes) and nanodevices (nanosensors and nanoelectronics). The reports of Bcc Research (Nanotechnology - A realistic market assessment) allow perceiving the outstanding extent and impact that nanotechnology has in various markets. Figure 1 shows the evolution of global nanotechnology market between 2009 and 2015. It shows a remarkable increase of approximately 122% between 2009 and 2015, mainly explained by commercialization of nanomaterials, such as nanotubes and NPs. These values are mainly explained by the potential of nanostructures and nano-modifications of materials that may lead to completely distinct composite materials, both at a macroscopic scale and in their properties and performance.

Considering all the markets where nanotechnology plays an important role, the construction industry certainly is not one of the markets where the impact is higher.

![Figure 1 - Global nanotechnology market evolution between 2009 and 2015 (values obtained from Report NANO31D - Bcc Research).](image)

In fact, due to the tendency of the construction industry to be fragmented, rationally more conservative and associated with less funded research, the implementation of nanotechnology in this industry is slower than in others. In addition, the construction industry stakeholders often perceive nanotechnology as expensive and too complex to explain. For those reasons, all the nanotechnology advantages have been precluded by the need to build a structure “as soon and economical as possible”. However, as many authors stated (Lee et al., 2010; Zhu et al., 2004), NMs will have in the short term a greater impact in the construction industry than in any other industry area. The potential to apply NMs in construction involves almost all technical areas within this industry, as shown in Figure 2. It shows that composites (polymeric, ceramic and metallic) and coatings take great advantage from the application of nanotechnology. However, concrete plays an important role, with the potential to develop new products with increased mechanical properties, more durable and with reduced pollution effects. Considering these aspects, this study focused the application of nanotechnology in the following materials for structural applications: (i) cement and concrete, (ii) polymers, and (iii) ceramics.
3. State-of-the-Art

3.1 Cement and concrete

Concrete is the leading material in structural applications, where stiffness, strength and cost play a key role in its capabilities. Typical concrete consists of Ordinary Portland Cement (OPC), inert materials such as sand, coarse aggregates and additions, admixtures and water. The main concern regarding the massive production of concrete concerns its main constituent: cement. Mehta and Monteiro (2010) presented two major challenges that the industry of production of concrete has to face in the following years: the environmental impact that the production of concrete has in terms of natural resources and pollutants emissions; the long-term durability and civil infrastructure deterioration. Nanotechnology may play an important role to face these challenges.

This topic focused the potential of using NMs as additives in concrete production. The techniques developed in this nanotechnology field have as their main purpose the manipulation of concrete’s structural composition in order to improve the performance of bituminous and cementitious products. These improvements have been achieved, to a great extent, by the addition of NPs in cement and concrete’s matrix constitution. To the author’s best knowledge, the most effective NPs for concrete production are: nano-silica and silica fume; titanium dioxide; nanoclay; carbon nanotubes, and graphene oxide. The following paragraphs summarize the most valuable progress in the nano-modification of cement-based materials and their influence on concrete behaviour. The advantages of using NPs have impact mainly in the following topics:

- Enhancement of concrete (compressive and flexural) strength;
- Reduction of the total porosity
- Acceleration of C-S-H gel formation;
- Enhancement of Young’s modulus;
- Environmental pollution remediation, self-cleaning and self-disinfection.

From all the nanomaterials presented, nanosilica (NS) seems to be the more advantageous nanomaterial when production of high compressive strength concrete is needed. Due to the chemical effect triggered by the pozzolanic reaction of silica with Calcium Hydroxide (CH) (Singh et al., 2013; Chong et al., 2012) and the physical effect due to the nano dimension of NS NPs, it is possible to achieve an increase of compressive and flexural strength of concrete up to 75% (Shakhmenko et al., 2013; Jalal et al., 2012). Also more uniform, denser and compact products were registered with the addition of these types of NPs. For that, an addition not higher than 10.0 wt% of NS should be considered. However, due to their great surface energy, NPs are easy to agglomerate explaining why large quantities of these NPs
cannot be uniformly dispersed. In this context, some authors (Martins and Bombard, 2012; Senff et al., 2010) suggested that the agglomeration of NS NPs may repel the cement particles around them causing an increase of the voids volume and a decrease of workability, suggesting the use of superplasticizers. Still, the advantages of the use of NS in concrete production are becoming well established, as the production of Cuore Concrete (Pascal Maes, 2014) demonstrates.

Beyond the use of NS, carbon nanotubes (CNTs) can also play an important role in this issue. CNTs, with its tubular nanostructure with a diameter of a few nanometers and a large length/diameter aspect ratio, have highly advantageous properties. It is widely accepted that CNTs have a Young modulus around 1.0 TPa (Sinnott and Andrews, 2001), which is five times higher than that of steel (Silvestre et al., 2012) and a tensile strength around 50-100 GPa. In research, two types of carbon nanotubes were reported: single-walled carbon nanotubes (SWCNT) and multi-walled carbon nanotubes (MWCNT), whose differences remain mainly in their overall thickness (Figure 3).

![Figure 3 - Conceptual diagram of single-walled carbon nanotube (SWCNT) (A) and multi-walled carbon nanotube (MWCNT) (B) delivery systems showing typical dimensions of length, width, and separation distance between graphene layers in MWCNT (Reilly, 2007).](image)

However, MWCNTs have the advantages of being less expensive and easier to produce with its multiple walls, which may justify their wider applications (Soliman et al., 2012) in strengthening other materials.

In terms of concrete properties, the addition of small contents of CNTs (0.0-0.1 wt%) may have great impacts in flexural strength (up to 25%), Young’s modulus (up to 50%), reinforce the nanostructure (decrease in nanoporosity) and increase C-S-H production (Konsta-Gdoutos et al., 2010b; Metaxa et al., 2009; Shah et al., 2009). In addition, CNTs can also increase the conductivity of cementitious materials, adding to the fact that cement-based materials are also piezoresistive which means that excellent sensors can be produced for concrete structures monitoring, as the studies of Li and Chou (2004) and Dharap (2004) support.

However, to achieve these improvements it is necessary to guarantee an appropriate dispersion of CNTs in the mixes, which cannot be always ensured. In fact, this is an important cause of a decrease in some of concrete properties (flexural and compressive strength) registered in some studies (Musso et al., 2009; Saéz de Ibarra et al., 2006).

On the other hand, when environmental pollution remediation, self-cleaning and self-disinfection issues are taken into account, titanium dioxide NPs (TiO₂) are definitely the NMs with more advantages. Combining TiO₂ NPs with cement-based construction materials seems to be a good solution, due to its
strong photocatalytic activity, which results in (i) an environmental pollution remediation, (ii) self-cleaning and self-disinfection, (iii) high stability and (iv) relatively low cost (Hashimoto et al. 2005). With the addition of TiO\textsubscript{2} NPs up to 20.0 wt\%, a NO\textsubscript{x} degradation up to 65-80% was registered for concrete samples. In fact, “self-cleaning” and “depolluting” concrete products with TiO\textsubscript{2} NPs are already being produced and used in some facades of buildings and in paving materials for roads, namely in Europe and Japan (Sanchez and Sobolev, 2010). One of the most known applications of self-cleaning concrete took place in the “Dives in Misericordia” church in Rome, completed in 2003 (Figure 4).

Figure 4 - The “Dives in Misericordia” church, constructed of TiO\textsubscript{2}-containing self-cleaning cement (Pacheco-Torgal and Jalali, 2011).

Nevertheless, other NMs have come up in recent research works such as graphene oxide, but its high costs are also an issue barring its incorporation in the construction industry, in addition to the costs of CNTs. It is expected that costs will decrease over time, as manufacturing technologies and demand increase. It is a challenge to the construction industry to solve production and distribution problems to provide solutions to the general public at reasonable costs.

### 3.2 Polymer nanocomposites

Polymers have become increasingly important in the construction industry in the past decades with expanding applications. Initially, unreinforced polymer composites materials were used in non-load bearing applications. The introduction of reinforced polymer composites extended the range of application of these types of materials. Today, the construction industry is one of the world’s largest consumers of polymers composites. The use of composites materials can significantly reduce the building’s dead load, which allows a weaker foundation, a more manageable seismic design and smaller construction crane requirements. This results in material and cost savings. Currently, fibre reinforced polymers (FRP) are probably the most used polymer matrix-based materials within the construction industry. The developments made over the years enabled the use of FRPs as structural elements in construction. Currently, the use of FRP for strengthening and repair existing structures is well established (Humphreys, 2003), such as CRFP to reinforce columns. Taking advantage of these opportunities, polymer matrix based nanocomposites (PMCs) have become a prominent area of research and development. The opportunity to apply PMCs in structural reinforcement and rehabilitation of damaged infrastructures, as well as working as new structural materials with increased load-carrying ability, justifies the increasing number of studies and publications, which largely increased from 204 in 2000 to 8034 in 2013.
While the improvements in mechanical properties in PMCs by nanomodifications are the primary area of interest, several other properties and potential applications are relevant such as barrier properties, flammability resistance or improved electrical/electronic properties (Pauls and Robeson, 2008).

According to the author’s best knowledge the most effective NPs to use in PMCs are:

- Nanoclay;
- Carbon nanotubes;
- Graphene;
- Nanosilica;
- TiO$_2$.

Still, regarding this particular industry, nanoclay, carbon nanotubes and nanosilica seem to be ahead in the use in PMCs systems. Thanks to their relatively low cost production, availability and particular properties, nanoclay is still the most studied NM. Much of the work that has been performed with NS in PMCs is related with modifying filler adhesives, reinforcement of polymeric films and epoxy matrices and incorporation in coatings production. In terms of epoxy matrices coatings, improvements up to 40% in hardness, facture toughness up to 5% and enhanced anticorrosive performance (barrier in a chloride-ion-rich environment) were obtained by various authors (Conradi et al., 2014; Ghanbari and Attar, 2014; Allahverdi et al., 2012). These improvements were achieved for small additions of NS up to 3.0 wt%. This opens the opportunity to apply these coatings in different surfaces such as steel, increasing its protection under harsh environments. Beyond coatings, improvements in thermal behaviour, elastic modulus (up to 28%) and elongation at rupture (20% lower) were also registered for polymeric foams with the addition of NS up to 5.0 wt%.

Structural nanocomposites may also take advantage of nanotubes’ superior mechanical properties as well as their high aspect ratio and surface area. Its application may range from adhesives to thermal and insulation materials. Moreover, embedding CNTs in the matrix of composite materials for damping augmentation by energy dissipation of these composites has been widely focused. From the perspective of reinforcement of existing structures, using CNTs in adhesives production may increase 13-20 times cracking under cyclic loads and its use in epoxy resins may increase up to 2.25 times the tensile strength and 3.27 the deformation at failure (Rousakis et al., 2014; Soliman et al., 2012). These resins may be used in crack repair of concrete members as well as in FRP sheet wrapping. The great potential of using CNTs is the small contents needed for these improvements, which should be under 2.0 wt% in the cases previously presented. On the other hand, the damping effect of matrix-embedded CNTs in fibre-reinforced composites has been offering the potential to design a passive damping mechanism into functional materials. For example, Koratkar et al. (2003) observed approximately 200% increase in damping ratio by addition of 0.05 nanofilm of MWCNTs in a piezo-silica composite beam.

Regardless of this great potential, the main concern regarding the use of CNTs remains on the levels of dispersion achieved. This is in fact the main challenge that research community has to face for a wider use of CNTs in PMCs.

Finally, nanoclay should also be considered in PMCs production. In addition to the mechanical, physical and thermal improvements that these NPs allow, the relatively low cost of clay minerals, their availability and unique characteristics justify the interest of the research community. Regarding mechan-
ical properties, Shokrieh et al. (2012) obtained an increase of 15.2% of the compressive strength for 3 wt% clay replacement and also an increase of 7.6% of the fracture toughness for an optimum value of 5wt% replacement (Figure 5a and Figure 5b). Also epoxy coatings with nanoclay have been tested for surface treatments and protective systems for concrete substrates, showing a decrease in porosity of more than 10% and an increase up to 30% in water vapour barrier properties (Scarfato et al., 2012).

(a) (b)

Figure 5 - Results of: (a) ultimate compression strength vs. nanoclay content. (b) fracture toughness vs. nanoclay content. (Shokrieh et al., 2012).

3.3 Ceramic nanocomposites

Ceramic materials are extremely valuable for applications with demanding thermal and mechanical requirements. Monolithic ceramics have attractive properties like stiffness, strength and stability at high temperatures. However, monolithic ceramics tend to be brittle, mechanically unreliable and poor electrical conductors, which has limited their use and expansion for years.

This topic focused the recent developments on ceramic matrix nanocomposites (CMCs). As previously described, CMCs have been less researched than PMCs, but there has been a recent increasing interest on this type of composites. CMCs can be extremely valuable for applications with demanding thermal and mechanical requirements. CMCs opened new possibilities such as the ability to achieve a damage-tolerant quasi-ductile fracture behaviour, maintaining all the other advantages of monolithic ceramics at high temperatures. Moreover, authors reported remarkable improvements in properties like hardness, stiffness, toughness, strength, damping and thermal conductivity over monolithic ceramics using nano fillers. For example, in the case of alumina CMCs, Fan et al. (2006) reported an improvement of approximately 100% in fracture toughness and 20% in flexural strength with the addition of only 1 wt% SWCNTs. Moreover, Walker et al. (2011) reported an increase of approximately 235% (from ~2.8 to ~6.6 MPa) at ~1.5% graphene platelets volume fraction. According to authors’ knowledge the most important fibres manipulated at nanoscale are:

- Silica Carbide (SiC);
- Zirconia;
- Carbon Nanotubes (SWCNTs and MWCNTs);
• Graphene.

In terms of thermal behaviour, fracture toughness and chemical resistance, silicon carbide, zirconia and alumina show more consistent results. Their incorporation in ceramic matrix has as primary impact an improvement of the microstructural composition with high densification, low grain growth and elimination of porosity. Consequently, it impacts other properties. For example, SiC shows potential to increase the thermal behaviour up to a maximum of 35% for a 20 vol% addition. For additions under 20 vol%, both silica carbide and zirconia additions increase the fracture toughness up to 35% and 50-100%, respectively. Additionally to these improvements, the dispersion of these nanopowders in ceramic matrices is currently relatively controlled, justifying the investment of some manufacturers in producing these nanopowders, such as CoorsTek (2014).

Still, the biggest potential of development of hi-tech ceramic materials is the opportunity of adding carbon derived nanomaterials, particularly CNTs and graphene. Regarding CNTs, their incorporation has a tremendous impact on almost all properties of ceramic materials. For example, the results showed up to 310% increase in fracture toughness for 10 vol% addition of SWCNTs. Also the electrical conductivity can increase up to 45% with the addition of CNTs for 5-15 vol% addition. However, the dispersion of CNTs in ceramic matrices represents a critical issue that has been preventing further developments. CNTs tend to form agglomerations, acting as defects leading to stress concentration and premature failure (Figure 6).

![Figure 6 - SEM images of fracture surfaces of (a) agglomerated CNTs in a borosilicate glass matrix and (b) homogeneously dispersed CNTs in a silica matrix (individually pull-out CNT segments can be observed that may be related to possible toughening mechanisms) (Cho et al., 2009).](image-url)

The techniques used to process CMCs with CNTs have gradually provided better and more consistent properties compared to traditional powder processing methods. However, further developments are still required to develop higher quality samples in sufficient quantities to provide reliable results.

The problems related with the addition of CNTs enabled graphene to gain preference in the application in CMCs. The results indicate similar improvements in mechanical properties to those of CNTs, such as improvements up to 235% in fracture toughness for only 1.5 vol% addition. The authors focused much attention on describing the toughening mechanisms with the addition with these types of NPs. Also the electrical conductivity increased up to 172 S m\(^{-1}\). Despite these positive results, more research is needed in order to define optimal contents and processing methods to consistently achieve these improvements.
If these issues become increasingly more controlled and the impact in other mechanical properties (such as compressive strength, bending strength) becomes accurately estimated, it is possible to expect that ceramic materials can be introduced as a structural material in the near future. For example, Kaneko and Li (1992) have already introduced in early 90’s a feasibility study of structural systems (beams, composite beams and structural joints) made from ceramics. Since then, the discovery and the emergence of new high potential nanomaterials, such as CNTs in 1991 (Iijima, S. 1991) opened new possibilities that may provide further developments in this issue.

4. Conclusions and future developments

In general terms, it may be concluded that currently the greatest impact on the construction industry market is likely to come from the enhancement of the performance of materials. For example, the addition of nanomaterials in concrete production may have great impacts in terms of the mechanical properties, namely compressive and flexural strength. Moreover an increase of the anticorrosive performance (barrier in chloride-ion-rich environments) may impact the durability of concrete and its structural behaviour during its life cycle. On the other hand, the use of nanomaterials to produce adhesives and epoxy resins with increased mechanical properties opens the opportunity to further developments in reinforcing concrete and steel structures, namely bridges with different types of joints. From another point of view, it is expected that, in the medium to long-term, nanotechnology development will lead to truly revolutionary approaches to design and produce brand new materials and structures with much improved energy efficiency and adaptability. It is thus predicted that nanotechnology must follow the same long path that FRPs have in the last decades with great impact on the market of construction. For example, it is reasonable to expect that CNTs composites may be used in bridges construction with increased carrying load ability and reduced deformation, which constitutes an important step towards wider use of FRPs in bridges’ construction.

In the construction industry, the development range of products and solutions based on nanotechnology goes from concepts and ideas to products that are already commercially available. Closing the gap between laboratory achievements and the real-world suitability is the biggest challenge.

The impact of these solutions on the commercial market has been influenced mainly by limited product awareness within the industry, the traditionalism and skepticism of the construction industry, an excessive focus on the initial investment over life-cycle cost, and the environmental impact and safety.

The most important issues that need to be overcome are:

- Cost;
- Manufacturing;
- Health and environment;
- Skepticism of stakeholders and consumers.

Taking into account all the advantages and drawbacks, nanotechnology clearly has the potential to be the key to a brand new world in the field of construction and building materials. The key to development remains on the countries that decide to profit from this opportunity with investment in research and production of nanobased materials.
Based on the conclusions of this dissertation regarding the potential of nanomaterials to apply in the construction materials, Portuguese scientific research institutions, in particular the research units of IST, with focus on the new Platform for Nanotechnology and Materials (IST-NM) (https://fenix.tecnico.ulisboa.pt/investigacao/IST-NM), have the opportunity to take an important step forward in this issue, being ahead in terms of research and aligned with community “hot topics”. In this sense, the issues with the most potential and value to be developed in future projects of research are:

- In the short term, the application of nanosilica in cement and concrete production promises larger possibilities of studies addressing the mechanical behaviour of some structural elements, such as beams, columns or slabs;
- The most widespread applications in a few years’ time are predicted to be with nanotubes, due to their outstanding mechanical properties. For that purpose, a better knowledge of their capabilities and processing methods is needed;
- The area of coatings is currently the one with more known applications in the construction industry. Although it has lower impacts on the structural behaviour of buildings, the opportunity to give structures anti-corrosion protection, self-cleaning and depolluting effects should be considered;
- Nanosensors are also an interesting issue although a vast number of new publications and tests are required in order to be ready for large structural applications.

5. References

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