Nanotechnology in civil engineering

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2 authors:

Ali Akbar Firoozi
University of Botswana

Mohd Raihan Taha
Universiti Kebangsaan Malaysia

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Ali Akbar Firoozi

Department of Civil & Structural Engineering, Universiti Kebangsan Malaysia, 43600 UKM Bangi Selangor Malaysia
afiroozi@eng.ukm.my

Mohd Raihan Taha

Department of Civil & Structural Engineering, Universiti Kebangsan Malaysia, 43600 UKM Bangi Selangor Malaysia
profraihan@gmail.com

Ali Asghar Firoozi

Department of Civil & Structural Engineering, Universiti Kebangsan Malaysia, 43600 UKM Bangi Selangor Malaysia
mehran.firoozi@gmail.com

ABSTRACT

Nanotechnology is one of the most active research areas that encompass a number of disciplines, including civil engineering and construction materials. It seems to hold the key that allows construction and building materials to replicate the features of natural systems improved until perfection for millions of years. Traditionally, nanotechnology has been concerned with developments in most of the fields like microbiology, medicine, electronic, chemical, and materials sciences. However, the potential for application of many of the developments in the nanotechnology field in the area of construction engineering has been growing. The objective of this study is to review the role of nanotechnology in civil engineering applications. It also discusses the application of instruments to reach material properties of nano-scale. Furthermore, it has been observed that better understanding and engineering of complex structures made by cement, steel or composite materials at nano-level will definitely result in a new generation of construction materials with higher performance in strength, durability, and other properties.

KEYWORDS: Nanotechnology; Nano-material; Nano-level; Nano-science; Construction

INTRODUCTION

Nanotechnology is the re-engineering of materials and devices by controlling the matter at the atomic level (Roco et al., 1999). In other words, nanotechnology is a field that is dominated by developments in basic physics and chemistry research (Chong 2004), where the phenomena on atomic and molecular levels are used to provide materials and structures that perform tasks that are not possible using the materials in their typical macroscopic form. The evolution of technology and instrumentation, as well as its related scientific areas, such as physics and chemistry, is making the research on nanotechnology aggressive and evolutional (Chong 2002). Not surprisingly, it has been observed that expenditure on nanotechnology research is significant.

A more accurate definition of nanotechnology was presented in 1981 by Drexler (Drexler 1981), such as the production with dimensions and precision between 0.1 and 100 nm. In medium terms, nanotechnology involves the study at microscopic scale (1 nm = 1×10^{-9} m). As a comparison, one must realize that a strand of human hair has 80,000 nm thickness and that the DNA double helix has 2 nm diameter. Between 1997 and 2003, the investment in nanotechnology increased at 40%, reaching up to 35,000 million Euro (Andersen et al., 2007). Some estimates predict that products and services related to nanotechnology could reach 1,000,000 million Euro per year beyond 2015 (NSF 2001). According to the report of RILEM TC 197-NCM, "Nanotechnology in construction materials" (Zhu et al., 2004), is the first document that synthesis in a clear manner the potential of nanotechnology in terms of the development of construction and building materials, namely:

- The use of nano-particles, carbon nano-tubes, and nano-fibers to increase the strength and durability of cementitious composites, as well as for pollution reduction.
- Production of cheap corrosion free steel.
- Production of thermal insulation materials with performance of 10 times the current commercial options.
- Production of coats and thin films with self-cleansing ability and self-colour change to minimize energy consumption.

In nano-level, gravity becomes unimportant, electrostatic forces take over, and quantum effects come in. Furthermore, as particles become nano-sized, the proportion of atoms on the surface increases relative to those inside, and this leads to novel properties. Current researchers dealing with nano-science and nanotechnology are exploring these novel properties since at nano-scale, we can alter the macro-properties and produce significantly new materials and processes. Discussion on the application of nanotechnology in civil engineering, specifically in construction, is extremely important. According to a study by the Canadian Program on Genomics and Global Health (CPGGH), nanotechnology in civil engineering was ranked 8 of 10 applications that most likely have an impact in the developing world (ARI News 2007).

Nanotechnology, therefore, allows the design of systems with high functional density, high sensitivity, special surface effects, large surface area, high strain resistance, and catalytic effects. All attributes are directly or indirectly the result of the small dimensions of nano-particles (Parviz 2011, Teizer 2012).

APPLICATION OF NANOTECHNOLOGY IN CONSTRUCTIONS

Many disciplines of civil engineering, including design and construction processes, can be benefited from nanotechnology. These include products that are for: Lighter structure, Stronger structural composites, e.g. for bridges and others. Low maintenance coating, Improved pipe joining materials and techniques, Better properties of cementitious materials, Reduced thermal transfer rate of fire retardant and insulation, Increased sound absorption of acoustic absorber, Increased reflectivity of glass, water repellents, nano-clay filled polymers, self-disinfecting surfaces, UV light protector, air cleaners, nano-sized sensors, and solar cells.

There are a large number of applications of nanotechnology in the construction engineering/industry. Some of these applications are examined in detail below.

Nano-cement

Portland cement is the most widely used construction material. It can be argued that concrete utilizes nanotechnology because it contains nano-particles as its ingredients, including nano-water particles and nano-air voids. However, it is not the application of the technology at nano-level. If it is possible to create the technological tools and organize the amount and locations of these nano-ingredients in a scientific way, then, concrete can experience the advances of nanotechnology. Concrete is, after all, a macro-material, strongly influenced by its nano-properties and understanding it at nano level can provide the avenues for improvement of strength and durability. The particle size of cement can be reduced to nano-size or can be modified by adding nano-tubes and reactive nano-size silica particles. A number of investigations have been carried out to develop smart concrete using carbon fibers (Chong et al., 2002) and it has been found that instead of carbon fibers, nano-carbon tubes added with nano-cement are more effective.

Nano-composites

Nano-composites can be developed by using nano-tubes, which can implant some of the outstanding properties of the nano-tubes. Alumino-silicates are mixed with carbon nano-tubes, which can produce strong and durable conductive films. Furthermore, the current sizes of alumino-silicates (50 to 100 nm) can further be reduced to 5 to 10 nm range, and a little volume percent of nano-tubes ($\approx 0.5\%$) can produce extraordinary composites. Besides, fibre wrapping that has been commonly used to strengthen the existing concrete structures has witnessed advancement by using fibre sheet (matrix) containing nano-silica particles and hardeners (Ge et al., 2008). These nano-particles penetrate and close small cracks on the concrete surface and, in strengthening applications, the matrices form a strong bond between the surface of the concrete and the fibre reinforcement. A detailed discussion on the different types of nano-cement composites is presented later.

Mineral and Metal Nano-materials to Improve Resistance to Biological Agents and Fire

A part from the structural change caused by heat-treatment, fungicide property of some minerals at nano-scale can also improve the biological durability of wood and wood-composite materials. In this regard, wollastonite nano-fibers (NW) have been reported to substantially improve the durability in poplar wood (Karmi et al., 2013). NS, NC, and nano-zinc oxide have also been reported to improve the resistance to Trametes versicolor, a white-rot fungus (Akhtari et al., 2013). Nano-silver and NW have also been reported to significantly improve fire-retarding properties in solid woods and wood-composite materials (Taghiyari et al., 2012, 2013). The high thermal conductivity coefficients of NS and NW materials have been reported to primarily transfer heat throughout the body of wood, preventing accumulation of heat over the surface layer, and eventually decrease the temperature below the ignitability of wood components. Furthermore, as a mineral material, NW helps fire resistance in a second way by acting as an impermeable physical barrier towards flame. NW forms a fire barrier towards the penetration of flames into the body of wood structure. In this sense, NW acts similarly to intumescent paints.

Nano-coatings for Concrete

In order to protect the structures/components from abrasion, chemical attack and hydro-thermal variations, and to improve aesthetics, chemical coatings are generally and routinely used. Till date, technology which limits the size of coating materials in micrometer can enjoy great advancement by using nano-science and technology. Studies are being conducted on the types of nano-particles in various binders and their effectiveness on key properties related to concrete deterioration, and it has been reported that a solvent containing a low molecular weight epoxy resin and nano-clay particles has shown promising results. Nano-meter thick coatings are durable and could have self-cleaning and self-healing properties. Nano-scale roughness of the coatings has the property to repel water and dirt, and can outdate the existing 'non-stick' technology. Self-cleaning properties of a coating made using nano-particles would also help to keep the coated surface totally free of dirt and dust (Balaguru 2007).

Nano-steel

Steel has played a major role in the construction industry since past two centuries. Fatigue is a significant issue for the structures subjected to cyclic loading, such as in bridges, towers, and off-shore platforms. Fatigue failure can occur at significantly low stresses than the yield stress of the material and lead to a significant reduction in service life. Stress concentration is responsible for initiating cracks which triggers fatigue failure, and research has shown that the addition of copper nano-particles reduces the surface unevenness of steel, which then limits the number of stress risers, and hence fatigue cracking. Furthermore, it has been reported that vanadium and molybdenum nano-particles can improve the fracture problems associated with high strength bolts (Nippon 2005).

Bactericidal Capacity

One of the most important applications of materials with photocatalytical properties concerns the destruction of fungi and bacteria. Indoor fungi and bacteria proliferation has been one of the main causes responsible for construction materials degradation and also for health problems (Zyska et al., 2001; Bolashikov et al., 2009) because fungi are responsible for mycotoxins growth (Reboux et al., 2010). Saito et al., (1992) studied the addition of TiO_2 powder with an average size 21 nm (30% rutile and 70% anatase) to a bacterial colony. The results showed that 60–120 mins were sufficient to destroy all the bacteria. The authors stated that using bigger TiO_2 particles reduces bactericidal capacity and the best results are obtained with TiO_2 concentration of 0.01 and 10 mg/ml. Huang et al., (2000) also confirmed that using lower dimension TiO_2 particles led to faster bacterial destruction.

Nano-glass

Extensive research is being carried out (Mann 2011) on the application of nanotechnology to glass. It has been reported that Titanium dioxide (TiO_2) can be used in nano form to coat the glasses to import the sterilizing and anti-fouling properties of TiO_2. Recent researches in Geography, Geology, Energy, Environment, and Biomedicine are into glass as well. TiO_2 coating captures and breaks down organic and inorganic air pollutants by a photo-catalytic process. Furthermore, TiO_2 is hydrophilic and this attraction to water forms sheets out of rain drops, and thus, self-cleaning glass is present in the market.

Nano-particles for Fire Protection

The application of Portland cement based coatings for fire protection of steel structures is limited since it is thick, tends to be brittle, and polymer additions are needed to improve adhesion with steel surface. It has been found that nano-cement mixing with carbon nano-tubes (CNT) with cementious material to fabricate fibre composites has outstanding properties of high strength (Makar et al., 2003) and fire resistance.

Clay/polymer nano-composites

One of the most interesting interdisciplinary areas in civil engineering discipline is clay/polymer composites. This technology has received great attention in the area of nano-composites research. It offers tremendous improvement in a wide range of physical and engineering properties for polymers with lower percentage of filler. This nano-composite approach has advantages over the so called fiber reinforced composites in the low filler loading range. The basic phenomenon behind this technique is “bottom-up and top-down approaches”. In the bottom-up approach, the nano-materials are made from atoms or molecules (small to big) and by adopting this principle, molecules can be made to arrange themselves automatically into useful shapes and structures.

Clay/polymer nano-composites have improved physical and engineering properties, including fire retardancy, barrier resistance, and ion conductivity (Hutchison et al. 1996). This polymer composite technique can also be useful for water-soluble hydrophilic/hydrophobic functional monomer (Zakir et al. 2011) systems for the preparation of polymer/silicate hybrid nano-materials.

ENVIRONMENT

The effect of various nano-materials on natural environment is hotly debated in nanotechnology and environmental researches. Various ongoing investigations have focused on the uncertainty regarding the potential effects of materials that exist on nano-scale with properties that are different than when using the material on a micro or macro scale (NNI 2003). Some work in this regard shows that the potential effects may be minimal (Tong et al. 2007). As constructed infrastructure are provided in natural environment, all materials used in the construction and maintenance of these facilities need to be compatible to the natural environment and their effects on natural environment should not be negative. Typical potential problems in this regard include leaching of materials into groundwater, releasing materials into airways through the generation of dust, and exposing potentially harmful materials during construction and maintenance operations. The nanotechnology becomes a double-edged sword to the construction industry. More researches and practice efforts are needed with smart design and planning so that construction projects can be made sustainable, and therefore, save energy, reduce resource usage, and avoid damages to the environment.

COST

The costs of most nanotechnology materials and equipment are relatively high. This is due to the novelty of the technology and the complexity of the equipment used for preparation and characterization of the materials (Mann 2006). However, costs have been shown to decrease over time and the expectations are that, as manufacturing technologies improve, these costs may further decrease. Whether the expected decrease will render the materials as run-of-the-mill construction engineering materials will have to be seen, and depends largely on the benefits rendered through the application of these materials. Current opinion is that in special cases, the materials will enable unique solutions to complicated problems that cause them to be cost effective, which will lead to large scale application of these specific technologies. In other cases, the traditional methods for treating the problem may still remain the most cost effective. It is a challenge to the construction engineer to solve real world transportation infrastructure problems and provide a facility to the general public at a reasonable cost.

Microscopy Methods

The most important and popular instruments for the investigation of nano-scale in civil engineering are listed below.

Atomic Force Microscopy (AFM): AFM is a kind of scanning probe microscopes (SPM). SPMs are designed to measure local properties, such as height, friction, and magnetism, with a probe. AFM provides a 3D profile of the surface on a nano-scale, by measuring the forces between a sharp probe (<10 nm) and surface at a very short distance (0.2-10 nm probe-sample separation). The probe is supported on a flexible cantilever. The AFM tip “gently” touches the surface and records the small force between the probe and the surface. The AFM can be used to study a wide variety of samples (i.e. soil, concrete, plastic, metals, glasses, semiconductors, and biological samples, such as the walls of cells and bacteria).

Scanning Electron Microscopy (SEM): A SEM instrument shows the electron column, sample chamber, EDS detector, electronics console, and visual display monitors. The SEM uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens. The signals that derive from the electron-sample interactions reveal information about the sample, including external morphology (texture), chemical composition, crystalline structure, and the orientation of materials making up the sample. In most applications, data are collected over a selected area of the surface of the sample, and a 2-dimensional image is generated that displays spatial variations in these properties. Areas ranging from approximately 1 cm to 5 microns in width can be imaged in a scanning mode using conventional SEM techniques (magnification ranges from 20X to approximately 30,000X, spatial resolution of 50 to 100 nm). SEM is also capable of performing analyses of selected point locations on the sample. This approach is especially useful in qualitatively or semi-quantitatively determining chemical compositions (using EDS), crystalline structure, and crystal orientations (using EBSD). The design and function of the SEM is very similar to the EPMA and considerably overlap in the capabilities that exist between the two instruments.

X-Ray Diffraction (XRD): XRD can be used to look at single crystal or polycrystalline materials. A beam of x-rays is sent into the sample, and the way the beam is scattered by the atoms in the path of the x-ray is studied. The scattered x-rays constructively interfere with each other. This interference can be looked at using Bragg’s Law to determine various characteristics of the crystal or polycrystalline material. Measurements are made in Angströms, with 1 Angström = 0.1 nm. The use of XRD is often compared to the microscopy techniques. XRD avoids issues of representative samples and determines crystals as opposed to particles as discussed above. However, XRD can be time consuming and require a large volume of sample.

Transmission Electron Microscopy (TEM): TEM uses an electron beam to interact with a sample to form an image on a photographic plate or specialist camera. High-Resolution TEM

(HRTEM) looks at the interference of the electron beam by the sample rather than the absorbance of the beam as with ordinary TEM. This gives a higher resolution, which is beneficial when studying nano-scale samples. However, it does require the understanding of the sample to allow interpretation of the results, as the phase-contrast resulting information can be difficult to interpret. This can, therefore, restrict the use of HRTEM.

Photon Correlation Spectroscopy (PCS): PCS measures the scattered pattern produced when light is shown through a sample. It combines this with calculations of the diffusion caused by Brownian Motion in the sample in a relationship described in the Stokes-Einstein equation. This will give the radius of a particle, and therefore, the estimation of the average particle size and distribution of particles through the sample. The sample must be a liquid, solution or suspension. It must also be very dilute or the scattering of light can be unclear. The technique is sensitive to impurities and the viscosity of the sample must be known. The range of particle sizes that can be measured has been quoted between 1nm - 10μm. An extension of this technique for higher concentration or opaque samples, such as emulsions, is Photon Cross Correlation Spectroscopy (PCCS). This can also be applied to nanoparticles.

Nanoindentation: Nanoindentation has become a commonplace tool for the measurement of mechanical properties at small scales, but many have even greater importance as a technique for experimental studies of fundamental materials physics. The most common use of nanoindentation is for the measurement of hardness and elastic modulus, and there has been considerable progress in the measurement of other mechanical parameters as well, including hardening exponents, creep parameters, and residual stresses. Such measurements have board application across the physical sciences, and there are several recent reviewers on the use of nanoindentation for property extraction. However, nanoindentation also lends itself to more fundamental inquiries in materials science. New capabilities in *in situ* and *ex situ* imaging, acoustic emission detection, and high-temperature testing are now being used to probe nano-scale phenomena, such as defect nucleation and dynamic, mechanical instabilities or strain localization, and phase transformation.

CONCLUSION

Based on the short review in this paper, nanotechnology has the potential to be the key to a brand new world in the field of construction and building materials. Although replication of natural systems is one of the most promising areas of this technology, scientists are still trying to grasp their astonishing complexities. Furthermore, nanotechnology is a rapidly expanding area of research where novel properties of materials manufactured on nano-scale can be utilized for the benefit of construction infrastructure, and a number of promising developments exist that can potentially change the service life and life-cycle cost of construction infrastructure to make a new world in the future.

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