Nanotechnology Applied to Create a New Generation of Multifunctional Construction Materials

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Abstract: Nanotechnology is a technology which uses particles whose size is a billionth part of a metre. Nanotechnology has become one of the most influential technologies in this century, since it is successfully applied in a growing number of industries, including construction industry, mostly in the production of construction materials. Among all the materials used in construction, concrete makes almost 70%. Nanotechnology has helped produce concrete of high performance properties. In the production of concrete, nanotechnology is used for producing and adding nanoparticles to concrete in appropriate proportions by appropriate methods.

This paper gives an overview of how nanotechnology is used to create multifunctional construction materials, such as a new generation of cement composite concrete, steel, glass, coatings, plastic, insulation, fire protection materials and others. The paper concludes with the review of benefits and challenges for a wider industrial application of nanotechnology in the construction industry.

Keywords: nanosilica powder, nanotitanium dioxide, nanoclays, nanocarbon tubes

Introduction

Nanotechnology was primarily developed in physics and chemistry, and is still developing under the name of nanoscience in these fields, but also in engineering. Generally speaking, nanotechnology is a technology that uses particles whose size is a billionth part of a metre, and nanoscience deals with measuring and characterization on the level of nano and micro structures of materials, with the aim to better understand the impact of such structures on properties on the macro level, as well as on the properties when structures are used by applying advanced techniques and by modelling on the atomic and molecular levels. Today, nanotechnology within nanoengineering is a part of applied science in almost all materials. In the construction industry it is mostly applied in the production of construction materials and in the protection from environmental effects, Figure 1. (1).

Nanoengineering uses materials and techniques of nanosizes with the purpose of producing multifunctional composite materials of superior mechanical properties and durability and also of considerably modified properties, such as low electrical resistance, self-sensing, self- cleaning, self-repairing, high ductility, self-control of cracking etc. So the key to nanotechnology is particle size, because material properties change under the influence of particle size in nanometres (10^{-9} metre).

<table>
<tr><td rowspan="11">Nanotechnology axes enable</td><td rowspan="5">Materials</td><td colspan="2">Structural materials</td><td>Non-structural materials</td></tr>
<tr><td colspan="2">Nanotech cement/ concrete</td><td>Glass</td></tr>
<tr><td colspan="2">Steel</td><td>Plastics and polymers</td></tr>
<tr><td colspan="2">Wood</td><td>Dry wall</td></tr>
<tr><td colspan="2">New structural materials</td><td>Roofing</td></tr>
<tr><td rowspan="6">Protection</td><td colspan="3">Filtration, Air purification
(Indoor air quality - Outdoor air purification)</td></tr>
<tr><td colspan="3">Coatings
Self-cleaning (Lotus-Effects - Photocatalysis), (ETC), Antibacterial</td></tr>
<tr><td rowspan="3">Energy</td><td rowspan="2">Reduction of energy consumption</td><td>Lighting</td></tr>
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VIPs - Aerogel - Nanogel and High performance day lighting - Thin-film Insulation - PCMs</td></tr>
<tr><td colspan="2">Electronics / Sensors</td></tr>
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Fig. 1 – Nanotechnology in construction materials (1)

When particles are nanosized, the proportion of atoms on the surface increases with respect to the atoms inside, causing nanoeffects which modify all known properties if the material is viewed macroscopically. The RILEM TC 197-NCM report, “Nanotechnology in construction materials” (2), is the first document which clearly defines the potential of nanotechnology in developing construction materials in the following fields:

- Application of nanoparticles, carbon nanotubes and nanofibres with the purpose of enhancing strength and durability of cement composites, as well as for pollution reduction,
- Production of cheap and corrosion resistant steel,
- Production of thermal insulation,
- Production of cladding, coatings and thin filaments with the property of self-cleaning, self-adhesivity and/or reduction of energy consumption

Also, according to (2) compared to the use in practice research has far advanced as shown in Tables 1 and 2.

Table 1 – Nanomaterial in research and application (2)

Awareness of nanorelated research and applications	% of those responded	
	Academics/ researchers	Industrial personnel
Understanding phenomena (e. g. cement hydration) at nanoscale	82	58
Nanoparticles, fillers and admixtures	80	37
Nanostructure modified materials (e. g. steel, cement, composites)	73	26
New functional and structural materials	61	26
Surface/ interface assessment, engineering	55	21
Special coatings, paints and thin films	45	21
Integrated structural monitoring and diagnostic systems	39	11
Self-repairing and smart materials	31	11
New thermal and insulation materials	20	11
Intelligent construction tools, control devices/ systems	22	11
Energy applications for buildings - new fuel cells and solar cells	24	0
Biomimic and hybrid materials	20	0

Table 2 – Application of nanotechnology by fields in the construction industry (2)

Involvement in nano-related activities which are potentially applicable to construction	% of those responded	
	Academics/ researchers	Industrial personnel
High performance structural materials	80	37
Understanding phenomena at nanoscale	69	21
Multifunctional materials/ components	40	11
Modelling/ simulation of nanostructures	38	5
Nanoscale techniques/ instruments	31	11
Smart materials and intelligent systems	29	16

This paper gives a wide overview of the use of nanotechnology in construction materials, cement composites, steel, glass, coatings, plastic, insulation, fire protection materials and other latest applications. A summarized table overview of nanotechnology in the construction industry is given in Table 3, and some basic, and according to authors, most possible applications in the construction industry are described in detail.

Table 3 – Review of nanoparticles and their application in construction industry (60)

Nano particles	Application areas
Nano-silica (SiO_2)	Replaces part of the cement to densify the concrete and gain early strength Improving pavement surface characteristics
Micro silica (silica fume)	Increase compressive strength and flexural strength in concrete
Carbon nanotubes (SWCNTs or MWCNTs)	Increase compressive strength and flexural strength in concrete It can be utilized self-sensing concrete for monitoring the structural conditions
Nanophosphorus	Improving road visibility
Nano TiO_2	Self-cleaning of concrete pavement
Polymer fibre matrix using nanosilica	Self-structural health monitoring system in repairs & rehabilitation
High performance steel using copper nanoparticles	In bridges for corrosion resistance & better weld ability
Nanotechnology enabled sensors	To monitor and control temperature, moisture, smoke, noise, stresses, vibrations, cracks and corrosion

Nanotechnology in cement composites

Cement composites are all composite construction materials in which cement is used as binding, coating, mortar and plaster and concrete. Concrete, as the most widely used material in the world, is a multiphase composite material whose properties change with time, therefore it should be investigated by using 4D approach. The amorphous phase of concrete, C-S-H gel, is a crystal structure, the size of crystals ranging from a nanometre to a micrometre, in concrete it serves as an “adhesive” by keeping other components of concrete together (3).

Nanomaterials can be added to cement composites in the following forms:

- Nanoparticles,
- Nanoreinforcements: nanofibres and carbon nanotubes.

According to literature (3-12), it can be stated that the application of nanosilica results in a multifunctional effect, as shown in Fig. 2 (11).

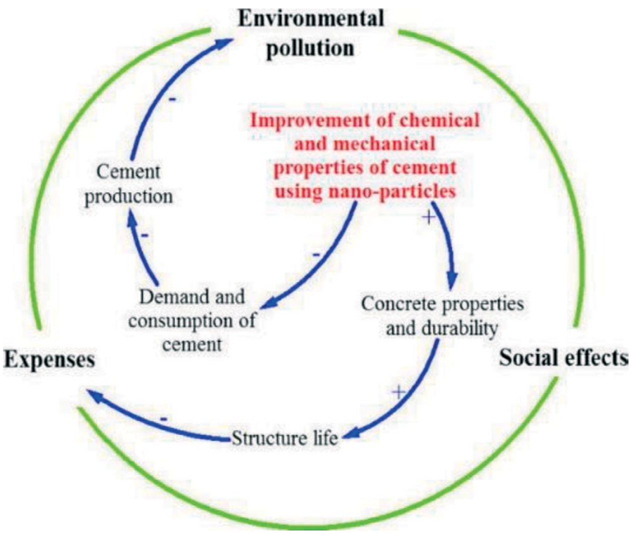


Fig. 2 – The role of nanoparticles in the sustainable development of construction industry (11)

Nanoparticles

Nano particles, Fig. 3, (3), have a large specific surface, and thus a large potential for physical-chemical reactions.

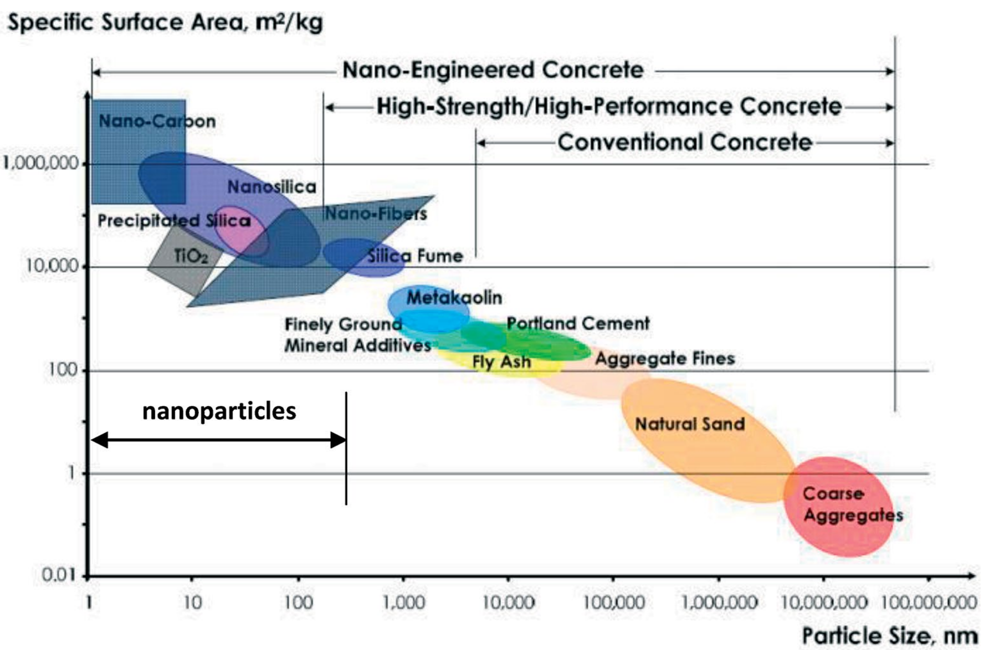


Fig. 3 – The size of particles and specific surfaces of concrete components (3)

Apart from the advantages of nanoparticles in cement composites there is one disadvantage, and this is a tendency to create nanoparticle aggregates, Fig. 4 (4). Therefore, it should be noted that every research into the impact of nanoparticles on properties of, e.g. cement composites, has emphasized the need for preliminary pre-treatment in special solutions and the dispersion of nanoparticles in water before they are added to the mixture of fresh composite. Dispersion is produced by a special method of using ultra sound waves, so called ultrasonification. Ultrasonification is an effective method of dispersing nanoparticles and, as can be seen in Fig. 5 (5), the method successfully breaks nanoparticle aggregates.

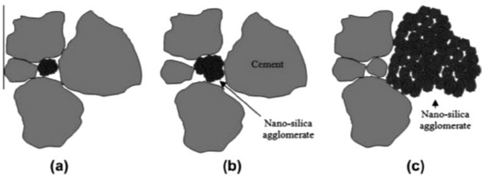


Fig. 4 – Illustration of the filling effect of nano-silica agglomerates (4)

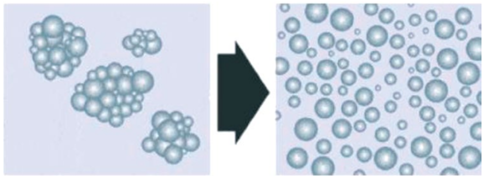


Fig. 5 – Dispersion and deagglomeration by ultrasonication (5)

Nanosilica powder

Silica powder is a by-product of producing silica and ferrosilicon alloys in electric arc furnaces, of a very fine granulation, and ranging from light to dark grey colour (3), Fig.6a.

Nanosilica powder or nano-SiO_2, Fig. 6a (6), with a very fine granulation, Fig. 6b (7), fills the gaps between C-S-H gel particles in cement composites, and acts as a nano-filler. Nano- SiO_2 does not only behave as a filler, filling a microstructure, but also as a

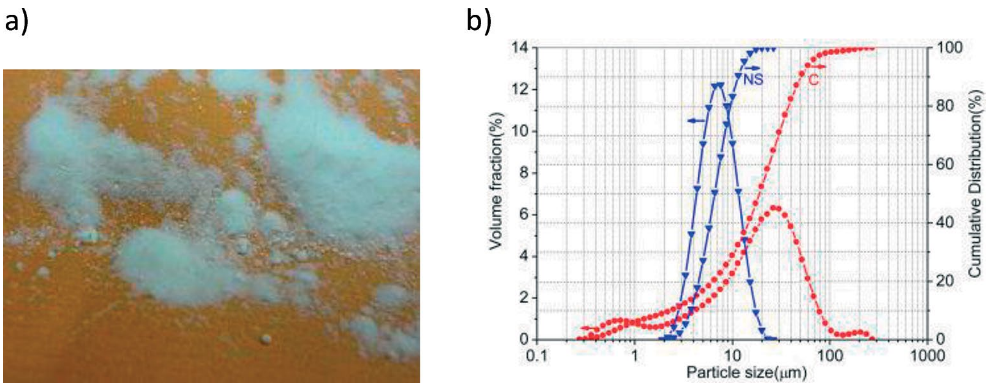
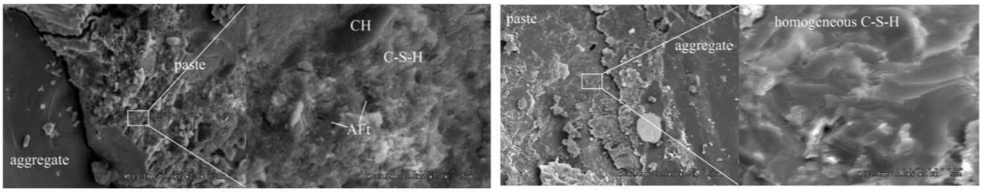


Fig. 6 –. Nano-silica, a) Nano silica sample (6), b) Particle size distribution of cement (C) and nano silica powder (NS) in laser diffraction analysis (7)

pozzolanic reaction stimulant. The pozzolanic reaction with calcium hydroxide increases the quantity of C-S-H gel, Fig. 7 (8), which results in higher matrix density, which increases workability, decreases porosity, increases strength and durability of the composite, increases impermeability and reduces the possibility of leaching (8, 9).



(a) OPC concrete (b) Concrete with 0.9% nano-silica

Fig. 7 – Microstructure morphologies at the interfacial transition zone (8)

Even the addition of small quantities of nanosilica, for instance, 0.25% in concrete, increases compressive strength by 10% and bending strength by 25%. Only 15 to 20 kg of nanosilica added achieve the same strength as 60 kg silica powder added (2). Still, the stated results largely depend on the manner of production and the conditions of nano SiO_2 synthesis, e.g. molar ratio of reagents, type of substances used for reaction, the duration of reaction of the so called sol-gel process and the dispersion of nano SiO_2 in cement paste.

Nanotitanium dioxide

Nanotitanium dioxide, nano TiO_2, Fig. 8 (12) has turned out to be very effective for self- cleaning of concrete and also has an additional positive impact on the environment. Photocatalytic efficiency of nanoparticles TiO_2 depends on different parameters, which will determine two basic processes of photocatalysis, that is, absorption of molecules of pollutant substances and the separation after absorption of UV photons (13, 14), Fig. 9 (14).

Fig. 8 – Nano TiO_2 powder (12)

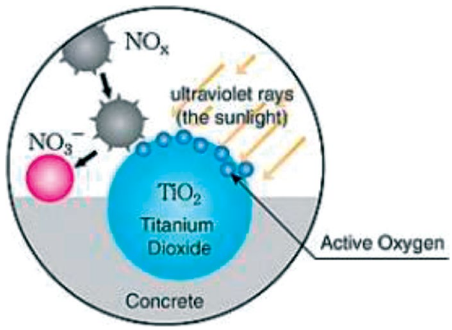


Fig. 9 – Photocatalytic cicle of nano TiO_2 activity (14)

Since the properties of absorption and charge separation depend on the basic properties of TiO_2 particles and the chemical properties of the pollutant, there is no universally acknowledged TiO_2 photocatalyst. Instead, there are many types of nano TiO_2 particles, each of different properties which make them variable, depending on the specific type of pollutant.

Concrete consisting of nano TiO_2 acts through photocatalysis to degrade traffic pollution and industrial emissions (3). The Italian concrete industry has produced white cement consisting of TiO_2 nanoparticles with photocatalytic properties which allow the maintenance of aesthetic features of architectural and decorative concretes over time with the additional benefit of removing pollutants. White cement containing photocatalytic self-cleaning nanoparticles has been used to construct the modernist church *Dives in Misericordia* in Rome, Fig. 10a, *Music and Art City Hall*, Chambery, France, Fig. 10b, *Via Porpora*, Milan, Italy, *Umberto I* tunnel, Rome, Italy, Fig. 10c, *Camden Council*, London UK, *Toyota Tsunami* plant, Saitama, Japan and others.

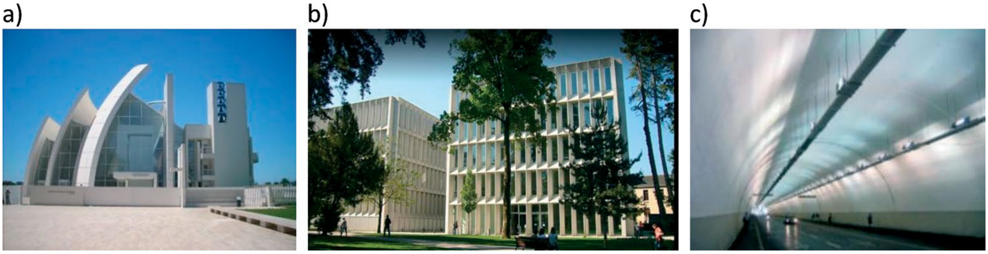


Fig. 10 – a) Church *Dives in Misericordia* in Rome, Italy (14), b) *Music and Art City Hall*, Chambery, France, (15), c) *Umberto tunnel I*, Rome, Italy (15)

In research (15) nano- modified Portland cement paste with water to cement ratio of 0.4, was prepared by adding TiO_2 nanoparticles of 0.1, 0.5 and 1.5 % per cement mass. Bending

strengths of the prepared composites were investigated, and breaking surfaces were observed afterwards by a scanning electron microscope (SEM). Bending strength of nano- modified TiO_2 Portland cement paste reached the highest value at dozes of 1.0% per cement mass. SEM scans show that the added TiO_2 nano particles considerably reduce the quantity of inner micropores in cement paste, and that nanoroughness of hardened cement paste with added TiO_2 nanoparticles is much lower compared to the ones without TiO_2, Fig. 11 (16).

According to (17-22) there is an increased use of nanotitanium dioxide in porous concretes on road surfaces for the purpose of reducing environmental pollution.

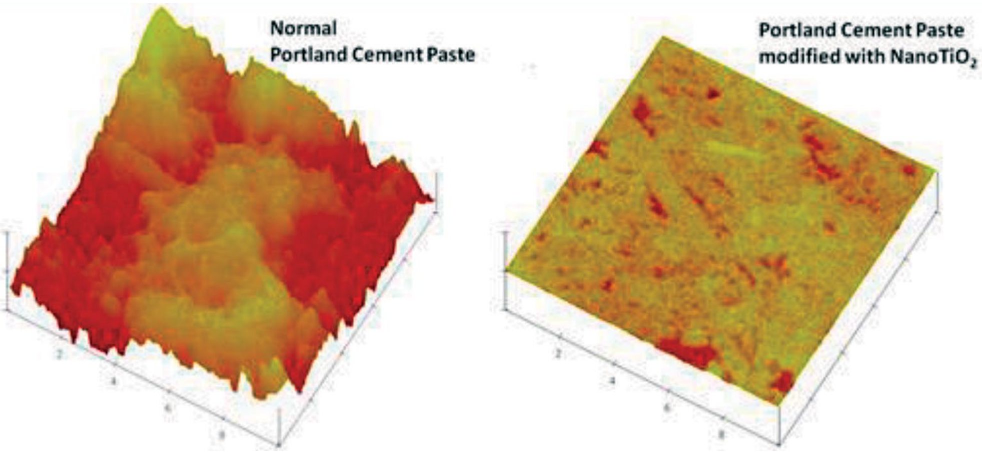


Fig. 11 – The surface nanoroughnes of cement paste on breaking surface after testing bending strength (16)

There are two efficient ways of introducing nano TiO_2 into concrete pavements which degrade exhaust gases from vehicles. One way is when nano TiO_2, together with concrete additives, is added to the concrete of the upper layer of pavement structures, and the other is when nano TiO_2, with added penetrates and dispersers, is sprayed over the surface of pavement structures. At present, there are several pilot projects of photocatalytic sidewalks, of which some are being planned and some have been built. One example is a highway section built in 2011 in St. Louis, MO, USA (18), and another one is in Japan, Fig. 12 (22). The trial sections will be monitored and compared with similar data collected throughout the year on the neighbouring part of the highway containing no nano TiO_2. The air quality will be also monitored on and near the highway on multiple levels. Testing in Europe has also shown that the material helps reduce smog in urban areas.


Fig. 12 – The use of TiO_2 photocatalytic material on a pavement structure for the purpose of reducing pollution in Japan, a) application of coating b) pavement structure with the lighter part where coating has been applied (22)

Research in (19) has shown that over time, as carbonization of concrete occurs, self-cleaning property is reduced, but further research is being conducted with the aim to find the effect of recreating self-cleaning property. Like nanosilica, the addition of nano TiO_2 to concrete accelerates early cement hydration, enhances pressure and tensile strength of concrete and increases wear resistance (3).

Nanoiron oxide

Nanoiron oxide, nano Fe_2O_3, when added to concrete, gives it the property of self-sensing. Detecting the change of electrical resistance while testing the compressive strength of concrete with added nano Fe_2O_3 has offered the possibility of monitoring concrete structures in real time by using the same principle (23). However, more extensive tests into the impact of nano Fe_2O_3 on concrete properties are required. Nazari and others (24) point out that, apart from the favourable effect on the compressive strength of concrete when nano Fe_2O_3 is added, concrete also loses its workability, and the percentage of optimal dosage has not been yet investigated.

Nanoaluminum oxide, nanozinc oxide and nanozirconium oxide

The addition of nano Al_2O_3, nano-ZnO_2, nano-ZrO_2 to concrete with an optimum dosage of 1 to 3% per cement mass improves the properties of fresh concrete by filler effect, and improves almost all properties of hardened concrete by pozzolanic reaction (25-27).

Concrete and reinforcement bond is fundamental in providing the behaviour of reinforced concrete elements, that is, in providing durability and ultimate limit states. In research (28) it has been concluded that the addition of Al_2O_3 and SiO_2 nanoparticles to concrete ensures the increased strength of bonding of concrete and reinforcement for the mixtures with a higher cement content (~ 300 kg/m^3). It has also been established that Al_2O_3 nanoparticles have a positive effect on reducing cracking.

Nanoclays

Nano clays are cheaper than other nanomaterials because the basic material comes from easily accessible natural resources and because they are produced in existing production plants. Organically treated clays are often used in many industrial branches due to their specific particle activity and attractive adsorptive properties. Organically modified montmorillonite clays (OMMT), which are widely used in polymer/clay nanocomposites (PCN), since the beginning of the 21st century have been intensively investigated as fillers and reinforcement in cement mortars (29). Namely, due to their hydrophilic properties montmorillonite nanoclays cannot be directly used in concrete because the water absorbed in interlayers between silicate boards cause unfavourable expansion, which can be extremely unfavourable and harmful to concrete. OMMT micro and nanoparticles modified by cation exchange become hydrophobic and as such suitable for use in concrete in which they enhance its strength and permeability. Research into the application of nanoclay in self- compacting concrete has shown that even in small doses (1%) concrete has the property of “spreading” and at the same time it is of a stable shape with a minimum flow loss (30). Nano clay particles improve the mechanical properties of concrete, its resistance to chloride penetration, Figs. 13, 14 (3, 27, 28), and the properties of self-compacting concrete regarding reduced permeability and shrinkage.

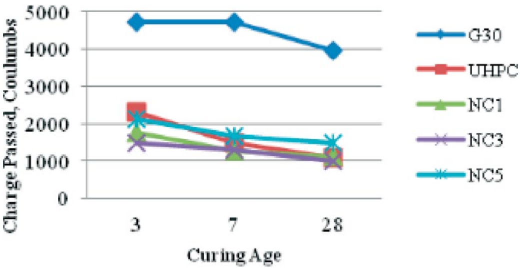


Fig. 13 – Chloride penetration in concrete without and with nanoclay (30)

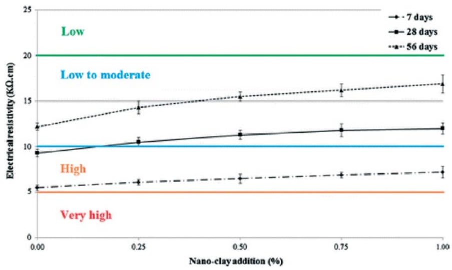


Fig. 14 – Electrical resistance of concrete without and with nanoclay added (31)

Nanocalcium carbonate

Nano $CaCO_3$ (NC) was first used in the form of a filler as a cement replacement, however, additional positive effects of $CaCO_3$ were proved regarding strength and hydration speed of cement composites. Engineering properties, including micro hardness and elasticity module, are largely improved in an early phase by adding nano $CaCO_3$ to concrete. It is evident that the size of nano $CaCO_3$ particles and C-S-H nucleation cause the development of mechanical properties (32). The paper (33) shows the testing of the effect of nano $CaCO_3$ (NC) on cement paste properties.

Experimental results have shown that NC has no effect on the need for water in normal consistency of cement. However, with the increased NC content heat is reduced and so is the time of fresh cement paste setting, Fig. 15 (33). Testing of mechanical properties has shown the increased bending strength and the compressive strength of hardened cement paste and the optimal content of NC was 1%.

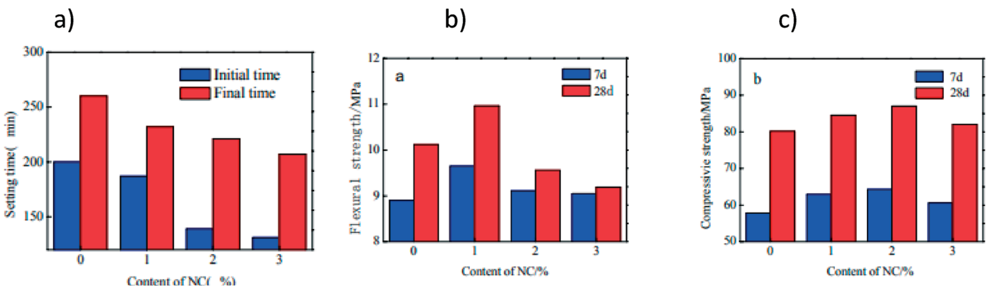


Fig. 15 – The effect of nano $CaCO_3$ on cement paste properties a) setting time, b) bending strength, c) compressive strength (33)

Testing of micro hardness of concrete also shows a considerable increase in micro hardness in concretes with mixed cement and nano $CaCO_3$, but more detailed research into the impact of nano $CaCO_3$ on deformation properties of concrete is required, since testings discussed in (34) owed increased shrinking.

Nanoreinforcements

In the last few years a number of materials for micro reinforcement were systematically investigated for the application in micro reinforced concretes. Nanoreinforcement properties of materials are summarised in (3) and in Table 4 (35).

Table 4 – Properties of nanoreinforcements (35)

Material	Elastic modulus (GPa)	Tensile strength (GPa)	Elongation at break (%)	Density (kg/m^3)	Diameter/ thickness (nm)	Surface area (m^2/g)
Graphene	1000	~130	0.8	2200	~0.08	2600
GO	23 – 42	~0.13	0.6	1800	~0.67	700 – 1500
CNTs	950	11 – 63	12	1330	15 – 40	70 – 400

Carbon nano tubes and nano fibres are potential materials for nanoreinforcement or nanoreinforcement of concrete. Fig. 16. (3, 35).

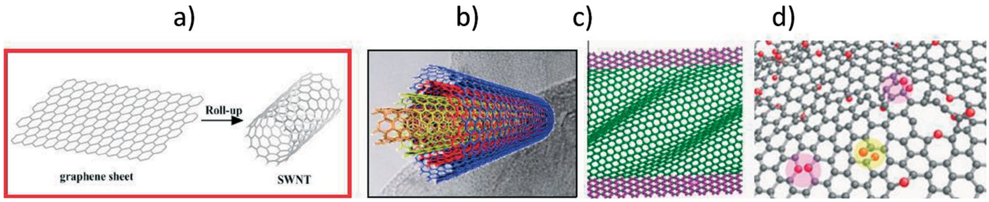


Fig. 16 – Carbon reinforcement, a) Single layer nanotubes, b) multi-layer nanotubes, c) wrinkled grapheme, d) grapheme oxide (GO) (3, 35)

Carbon nanotubes and nanofibres are of an extremely high strength, elasticity modulus and of unique electronic and chemical properties. All the above makes them the most promising nanoparticles, particularly as regards resistance to cracking, electromagnetic protection and self-sensing. Research into mechanical properties of nanocomposites conducted by testing bending at three points and by analysing by fracture mechanics and SEM scans (36) proved increased resistance to cracking, Figs. 17 and 18.

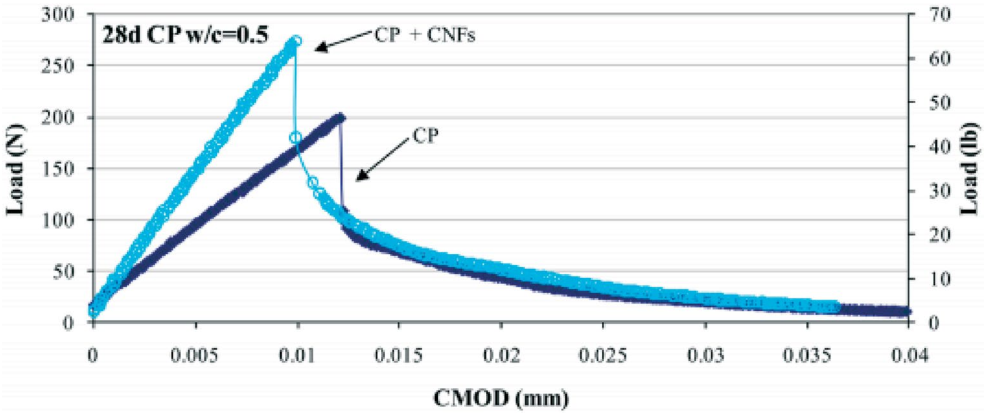


Fig. 17 – Load curves of CMOD cement paste without and with CNF (nanofibres) (36)

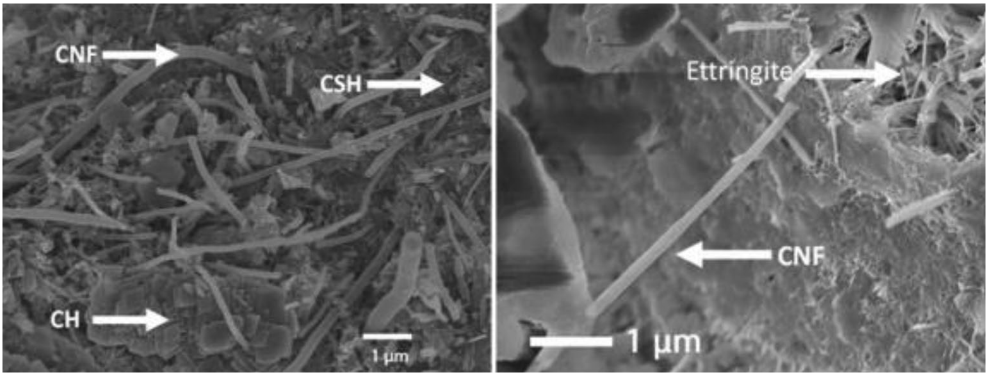


Fig. 18 – SEM scan of the fracture surface of the cement paste with added nanocarbon fibres (37)

Nanocarbon tubes, CNT, also have interesting electromechanical properties. When sample load varies, CNT will show electrical properties which change with the level of strain, showing linear and reversible piezoresistive response. Electromechanical properties of carbon fibres, CF, were irreversible due to fibre breakage when strain was higher than 0.2%. Since CNT properties are superior to the properties of CF, there is possibility of developing smart concrete with excellent piezoresistive response by using CNTs as additive. Recently Li and others used multi layered, chemically treated carbon nanotubes (MWNTs), to make piezoresistive composites based on cement and measured the piezoresistiveness of this composite under uniaxial pressure (38). According to their results and analysis, self-sensing CNT sensors were made and installed into a concrete pavement. Sensors were made from cement mortar with added piezoresistive MWNTs, and installed at definite distances into a concrete pavement, Fig. 19. Sensors have a considerable potential for traffic tracking, like finding vehicles, taking measures in motion and detecting vehicle speed.

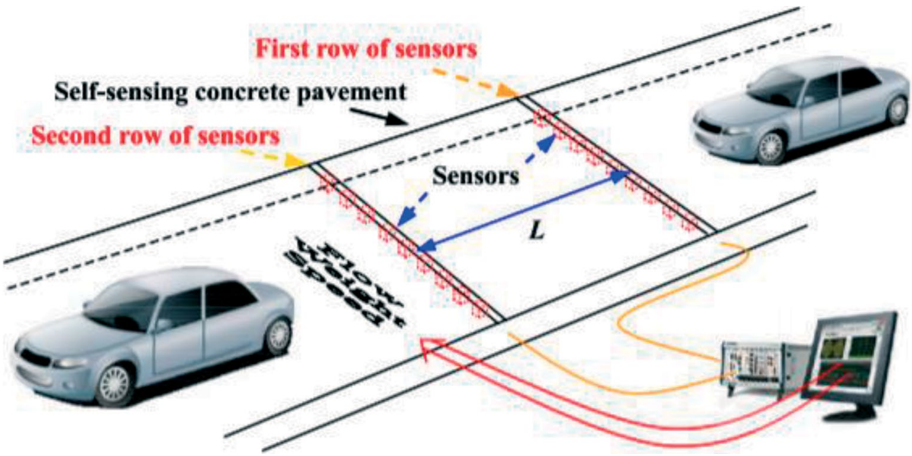


Fig. 19 – Traffic tracking on self-sensing concrete pavement (38)

Nanotechnology and steel

Steel has played an important role in the construction industry for the last two hundred years, and it still does today, which means that steel is one of the most important and essential materials in the construction industry (39). Although steel has a very good strength at tensile stress, it has problems with fatigue when cyclically loaded. Steel fatigue will decrease if copper nanoparticles are added. When copper nanofibres are applied to steel surface, the surface of finished steel becomes smooth and flat. The flat surface can reduce stress, and breaking caused by fatigue. A new steel generation also has higher resistance to corrosion. Two relatively new products are available today, SandvikNanoflex and MMFX2 steel.

They have very different mechanical properties and resulted from two different applications of nanotechnology. They are resistant to corrosion, have higher resistance to deformability and fatigue, and can help prolong the lifespan in corrosive environment and thus lower the costs in the life span of a building (41, 42). Fig. 20 shows the façade of a nanomodified steel building (40).

Fig. 20 – Nanosteel in facades (40)

Nanotechnology and glass

It is a constant problem how to clean glass. Glass with titanium dioxide is the best solution of this problem. Titanium dioxide dissolves organic waste, and rainwater or automatic sprinkling of facades with water cleans the dirt from glass facades and thus reduces maintenance costs, Fig. 21a (43). Also, nanotechnology is successfully used to produce fire resistant glass. Since TiO_2 has hydrophobic properties, it can be used in anti-fog coatings.

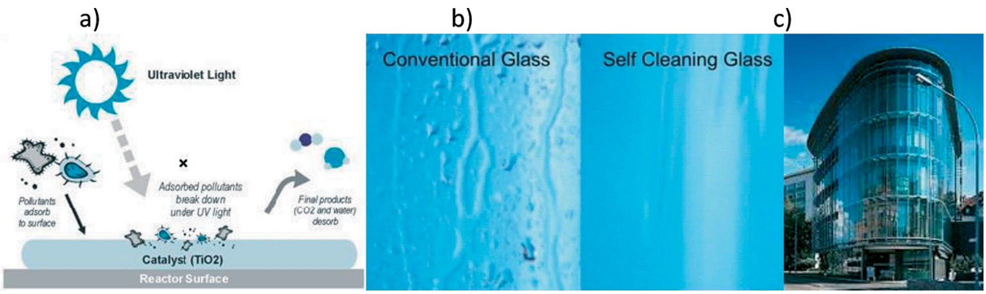


Fig. 21 – Self-cleaning glass, a) Process scheme (43), b) Glass with and without treatment (44), c) A self-cleaning facade (45)

Photocatalytic coating has a secondary use in warmer climates. Instead of waiting for rain, glass surfaces are washed by sprinkling water on glass surfaces which has a dual effect: windows are self-cleaned and the temperature inside the building is reduced. The International Narita Airport in Japan used photocatalytic membrane when its Terminal 1 was refurbished in 2006, Fig. 22a (14). The coating reduced cleaning costs.

Fig. 22 – Examples (14), a) The roof of Terminal 1, Narita International Airport, Tokyo, Japan, b) MSV Arena Soccer Stadium with Pilkington glass facade, Duisburg, Germany

Along with self-cleaning, antireflective properties are developed by use of SiO_2-TiO_2 coatings on glass beddings by applying the combined dual layer sol-gel tip coating process. These materials are practical to use since they are bifunctional, antireflective and self-cleaning. They are also suitable for large facades and particularly for solar cells, Fig. 23, (46, 47).

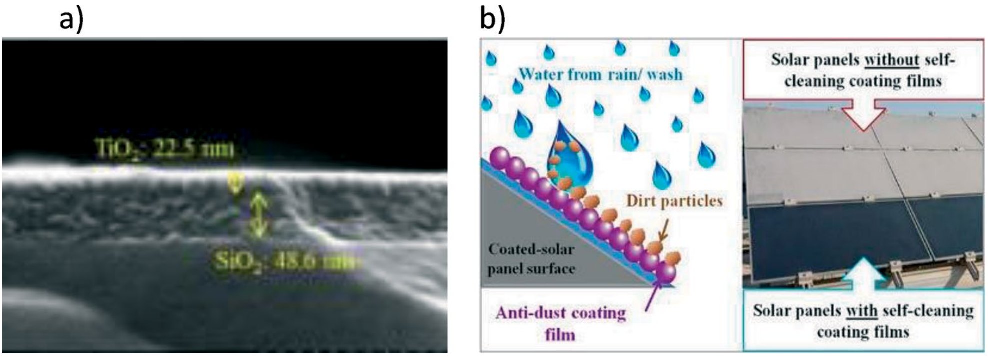


Fig. 23 – Glass with antireflective and self-cleaning properties, a) layer scan (46), b) Schematic view of the self-cleaning effect on solar panels in polluted regions (47)

Fire resistant glass is another example of applied nanotechnology. It is produced by using an interlayer which is heated through glass panels, and which consists of nanoparticles saturated with silica gel (SiO_2) (48). Also, thin layer coatings are being developed for use on window glass which has a potential to filter unwanted infrared light frequencies which warm up the space and reduce temperature in buildings (49).

Nanotechnology on wood

Carbon nanotubes are an innovative, new material, while wood is an ancient material which has been used since the very beginnings of the civilization. However, wood in its structure also has nanotechnology and wood can result in interesting uses. Strong waterproof coatings are used for wood, integrated nanoparticles, of silica and aluminium oxides with hydrophobic polymer (52), and as nanofungicidal coatings TiO_2 nanoparticles are applied on a wooden surface (53). The application of nanotechnology on wood has created self- sterilizing surfaces and internal electronic lignocellulosic devices (50), and successful trials to copy natural structures are shown in Fig. 24 (51).

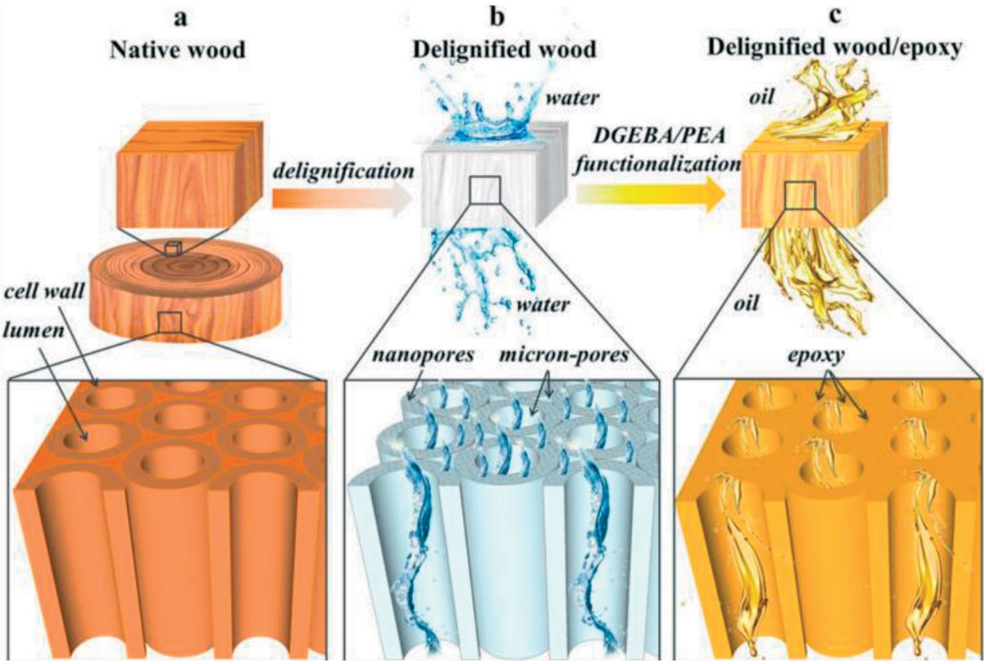


Fig. 24 – Schematic illustration of structural design of porous and functional wood materials for selective separation of oil-water mixtures: (a) native balsa wood, (b) delignified wood template, (c) delignified wood/epoxy biocomposite

Nanotechnology in coatings

Coatings also play an important role in the construction industry; in buildings coatings are widely used on walls, doors and windows, and in infrastructure facilities they are used as protection from moisture, corrosion and fire (54-57). Nanotechnology is used in coatings by adding nanoparticles which have been described above.

Nanotechnology in sensors

Nano and microelectromechanical systems (MEMS) were developed and used in structures with the purpose of following and/or monitoring the state of the environment and the properties of materials in structures. One of their advantages is their size (10^{-9}m do 10^{-5}m) (58). These sensors can be installed into an aggregate grain and/or into a structural element during the construction process, and they are used to monitor early-age properties of concrete such as moisture, temperature and the development of strength in the early phase (59). Sensors can also be used to monitor reinforcement cracking and corrosion.

Conclusion

Instead of a conclusion, a review of basic advantages and obstacles to the application of nanotechnology in construction is given. Although it should be said that nanotechnology has contributed to the strong development of construction materials, there are still numerous challenges in practice, and health and ecological issues are the most important ones that have to be investigated. It is known that nanoparticles can penetrate into human cells, so regardless of the beneficial effects of these materials, they also have negative and dangerous impacts on living organisms which must be identified and should be avoided and monitored by establishing effective methods.

Table 5 – Benefits and barriers for the use of nanotechnology in the construction industry (61)

Benefits	Materials and properties	Strength and durability (e.g. cementitious composites) Wear and tear resistance Corrosion resistance (e. g. coatings) Fire resistance and retardants Aesthetics Heat insulation (e. g. glass) Self-cleaning (e. g. concrete, glass) Bactericidal capacity (e. g. coatings) Photocatalytic activity - Promotes air pollution reduction (e. g. cements and coatings)
	Economic	Improves life-cycle and maintenance costs Pricing and profit Customer satisfaction Market value and brand image
	Sustainability	Energy efficiency Reduces material consumption Social and ethical benefits Reduced levels of several environmental pollutants (e. g. CO_2 associated with cement production) - “Green nano-construction”
Barriers	Costs and manufacturing	Costs of materials and equipment Costs of commercialization High initial investment by nanotechnology companies Lack of properly trained personnel and costs of training
	Environmental	Safety and security concerns Potential toxicity to the workers
	Social	Regulatory and legal issues Scepticism of the main industry stakeholders and consumers

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