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RILEM TC 197-NCM: 'Nanotechnology in construction materials'

Application of nanotechnology in construction

Summary of a state-of-the-art report

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1. ABSTRACT

The paper is an extended summary of the state-of-the-art report on Application of Nanotechnology in Construction, which is one of the main tasks of a European project – Towards the setting up of a Network of Excellence in Nanotechnology in Construction (NANOCONEX). The paper first presents background information and current developments of nanotechnology in general. Then, the current activities and awareness of nanotechnology in the construction industry are examined by analysing results of a survey of construction professionals and leading researchers in the field. This is followed by results of a desk study of nanotechnology development and activities focussing on key areas relevant to construction and the built environment. Examples of nanotechnology-enabled materials and products that are either on the market or ready to be adopted in the construction industry are provided. Finally, the future trend/potential and implications of nanotechnology development in construction are discussed.

2. INTRODUCTION

2.1 Background

Nanotechnology has recently become one of the 'hottest' areas in research and development worldwide, and has also attracted considerable attention in the media and investment community. It is essentially about new ways of making things through understanding and control over the fundamental building blocks (*i.e.* atoms, molecules and nanostructures) of all physical things. This is likely to change the way almost everything is designed and made [1]. With the backing of unprecedented funding, nanotechnology is fast emerging as the industrial revolution of the 21st century [2].

2.2 What is nanotechnology?

In contrast to other technologies, nanotechnology is much less well-defined and well-structured. Nano, which comes from the Greek word for dwarf, indicates a billionth. One nanometre is a billionth of a metre, that is, about 1/80,000 of the diameter of a human hair. Nanotechnology can best be considered as a 'catch-all' description of activities (any application of science and technology) at the nanometre scale that have applications in the real world [3]. Definitions of 'nanotechnology' vary, but it generally refers to understanding and manipulation of matter on the nanoscale, say, from 0.1 nm to 100 nm.

The significance and importance of controlling matter at the nanoscale is that at this scale different laws of physics come into play (quantum physics); traditional materials such as metals and ceramics show radically enhanced properties and new functionalities, the behaviour of surfaces starts to dominate the behaviour of bulk materials, and whole new realms open up for us [4]. Gaining control of structures at the nanoscale sometimes leads to truly extraordinary materials such as carbon nanotubes, with a tensile strength often quoted as 100 times that of steel.

There are two ways to approach the nanoscale: shrinking from the top down, or growing from the bottom up. These two models are fundamentally different, both in the approach to creating structures and in the underlying science that will make them possible [5]. The 'top down' approach entails reducing the size of the smallest structures towards the nanoscale by machining and etching techniques, whereas the 'bottom up' approach, often referred to as molecular nanotechnology, implies controlled or directed self-assembly of atoms and molecules to create structures. Nanoscience and nanotechnology inevitably cross the boundaries and bring together traditional sciences and technologies, such as chemistry, physics, the life sciences, materials and many engineering disciplines.

More than anything else, nanotechnology is an enabling technology, allowing us to do new things in almost every conceivable technological discipline. At the same time, its applications will lead to better, cleaner, cheaper, faster and smarter products and production processes. Just as other enabling technologies, *e.g.* electricity and microelectronics, have transformed lives, nanotechnology is likely to have a similar impact and the transformation may be much quicker due to the development of powerful computers, global communication and many other technological advances.

2.3 Historical development of nanotechnology

Nature has been manufacturing nanosized objects for billions of years, such as cells in plants and animals, but we do not call that nanotechnology. Also, nanoparticles can be found in Ming-dynasty pottery and stained-glass windows in medieval churches. But then people were not aware of the nanoparticles involved, and as they had no control over particle size or knowledge of structures at the nanoscale, they were not using nanotechnology as currently defined.

The concept of nanotechnology was put forward theoretically in 1959, by Feynman. The Nobel Prize winning physicist said that nothing in the laws of physics prevented us from arranging atoms the way we want. He even pointed to a development pathway: machines that would make smaller machines suitable for making yet smaller machines, and so on – the classic 'top down' approach [6]. In 1974, Taniguchi introduced the term nanotechnology to describe precision manufacture of parts with finishes and tolerances in the range of 0.1 nm to 100 nm [7].

In 1981, Drexler pointed out a new approach: construction of materials and devices from the 'bottom up' with every atom in a designed location [8]. Around the same time, Binnig and Rohrer at IBM invented the scanning tunnelling microscope (STM) which allowed scientists for the first time to view things (*e.g.* nanoparticles) at atomic resolution. Soon afterwards, the atomic force microscope (AFM) for working with non-conductive materials was also developed. Since then, a raft of related instruments now known collectively as scanning probe microscopes (SPMs) have been developed to analyse properties of nanostructures, molecules and atoms on the surfaces. The capability to manipulate and positionally control matter on a nanoscale was demonstrated, for the first time, in 1989 when Eigler used a SPM to slowly arrange 35 xenon atoms to spell out the letters IBM (spanning less than 3 nm) on top of a crystal of nickel.

The term nanotechnology was popularised by Drexler's book 'Engines of Creation' published in 1986 [9]. He envisioned tiny self-replicating molecular assemblers that could build everything from chairs to rocket engines and machines that turn domestic waste into foods and toys at a touch of a button, and nano submarines voyaging through our bloodstream zapping cancer cells. It is no wonder people often muddle up nanotechnology with science fiction. Although some of the visions of the future enabled by nanotechnology are quite speculative, they stem largely from quite straightforward ideas founded in solid science, and generally referred to as molecular nanotechnology [4].

Over the past decade, the focus of nanotechnology has broadened beyond physics and precision engineering to include 'almost any materials or devices which are structured on the nanometre scale in order to perform functions or obtain characteristics which could not otherwise be achieved' [10]. In 1999, nanotechnology received a major boost when the USA government created the National Nanotechnology Initiative (NNI) and started to pour huge amounts of funding into research areas related to nanotechnology. This was soon followed by unprecedented investment provided by many other governments, businesses and venture capitalists.

3. NANOTECHNOLOGY IN GENERAL

Over the last 5 years, a number of reports on nanotechnology development and opportunities have been published [1-5, 11-15]. The authors' intention here is not to provide a comprehensive analysis, but to present a general overview of the major research and commercialisation activities, and future trends in general. The application of nanotechnology in construction will be examined in more detail in the next section.

3.1 Funding of nanotechnology R & D

There has been an explosive growth of interest in nanotechnology over the last few years. The NNI in the US in 2000 was the catalyst to rapidly increasing funding and activities in this area. Global government spending on nanotechnology has more than doubled in the last 2-3 years, and has now grown to well over $2 billion a year.

There is also substantial money flowing into nano-related research from multinational corporations and venture capital investments [4, 16]. Many of the world's largest companies, such as IBM, Intel, Motorola, Lucent, Boeing, Hitachi, Mitsubishi, NEC, Pfizer, Corning, Dow Chemical, 3M, General Motors, Ford, etc. have all had significant nano-related research projects going on, or launched their own nanotech initiatives.

3.2 Research and commercial activities

Scientific publications and patents provide a useful indication of the nature and extent of research activities and technological advances in particular areas. Using the Science Citation Index (SCI) expanded database (at http://wos.mimas.ac.uk), it was found that the number of refereed publications has risen from a few hundred in 1990 to over 18000 in 2002, and is still increasing rapidly. Similarly, there has also been a rapid increase of nano-related patenting activity in the past few years.

The commercialisation of nanotechnology is being pursued in a very broad spectrum of industry segments and geographies. A survey of 227 companies worldwide conducted by In Realis during 2000-2001 appeared to indicate that about 40% of the companies were mainly in the materials sector, as shown in Fig. 1 [17]. Other major areas of commercial development were in electronics, biotech (comprising pharmaceuticals, healthcare, etc.) and tools. The assemblers category which covers the long-term objective of molecular nanotechnology (*e.g.* fabrication through self-replication), however, had little commercial application.

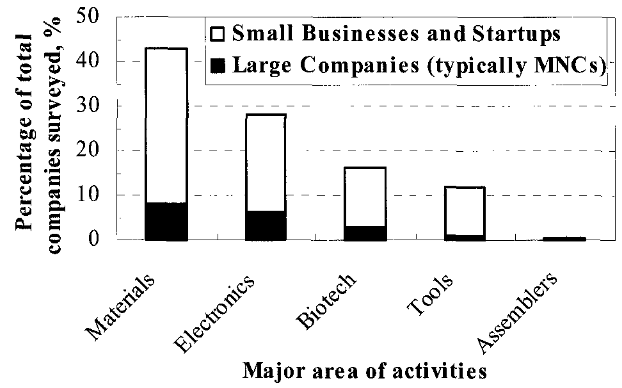


Fig. 1 - Profile of nanotech company focus (source: [17]).

To gauge the exact number of companies active in nanotechnology and the market value of the nano-products appears to be difficult since huge variations in the nano company numbers (from 250 to over 1300) and in the existing market sizes (from $100 million to $30 billion) have been reported. The very fast speed of new nanotechnology products and companies being created and coming to the market is thought to be one of the main reasons for the difference in statistics. Different methods and extent of the surveying, analysing and categorisation used also contributed to the discrepancy reported.

Some general common conclusions, however, could be drawn from the existing surveys and reports. These are summarised and presented below:

- Contrary to popular belief, in the vast field of nanotechnology, many industries already produce or employ products which are either nano-sized or exploit nano effects, and are generating substantial revenues. New viable products are being introduced almost daily, and the possibilities of nano materials/applications seem endless. The National Science Foundation (NSF) of the US predicts that nanotechnology products and services will generate revenues of $1 trillion per year by 2015 [14].
- The rate of commercialisation and growth of nanotechnologies, however, varies widely from industry to industry. Materials, manufacturing and tools/instrument sectors are expanding exponentially and generating most of the nano-related products and services revenues, while assemblers or molecular nanotechnology sector, in spite of significant research effort, has seen little commercial activity.
- Understanding properties and processes is a significant focus of research, highlighting that there is still much to learn about the nature of the new materials that can be engineered at the nanoscale.
- The greatest short-term benefit of nanotechnology may be in bringing together the disparate sciences and engineering disciplines. The rapidly increasing level of interdisciplinary activity in nanostructuring is growing in importance, and the intersections between the various disciplines are where much of the novel activity resides [2].

4. NANOTECHNOLOGY IN CONSTRUCTION

The construction industry was the only industry to identify nanotechnology as a promising emerging technology in the UK Delphi survey in the early 1990s [18]. The importance of nanotechnology was also highlighted in foresight reports of Swedish and UK construction [19-20]. Furthermore, ready mix concrete and concrete products were identified as among the top 40 industrial sectors likely to be influenced by nanotechnology in 10-15 years [17]. However, construction has lagged behind other industrial sectors, such as automobile, chemicals, electronics and biotech sectors, where nanotechnology R&D has attracted significant interest and investment from large industrial corporations and venture capitalists.

Recognising the huge potential and importance of nanotechnology to the construction industry, the European Commission in late 2002 approved funding for the Growth Project GMA1-2002-72160 "NANOCONEX" - Towards the setting up of a Network of Excellence in Nanotechnology in Construction. One of main tasks of the 12-month project was to produce a state-of-the-art report of nanotechnology in construction. The main objective of the state-of-the-art report was to evaluate current development, awareness and future potential of nanotechnology in the broad area of construction and the built environment. It also aimed at contributing to a long-term road map of nanotechnology in construction and supporting the setting up of a scientific programme of future proposals.

The report was prepared in two parts. The first part was based on results of an email survey of professionals and leading researchers in the construction industry. The second part was a desk study of worldwide nano-related activities and development relevant to construction and the built environment by analysing existing reports, publications and information available on the Internet.

4.1 Awareness and existing nano-related activities in construction

An e-mail survey, in the form of questionnaire and e-mail, was carried out in two stages. In the first stage, a simple questionnaire was sent to a targeted population of approximately 400 leading researchers, construction professionals, large companies involved in construction and nano-materials/tools manufacturers. In the second stage, two further questionnaires were sent to the 50 plus respondents selected from the first stage. The respondents were asked to provide detailed information on existing resources and relevant current research projects.

With the European project in mind, the majority (~90%) of the targeted were from European countries, and the remaining 10% mainly from US, Canada, Australia, Japan and China. Out of all the recipients of the questionnaire, 83 responded, a return rate of 21%. Due to only a few responses from outside of Europe, the survey results are likely to reflect mainly the current situation in Europe. Table 1 shows the distribution of respondents in different sectors related to construction and the built environment.

As the results in Table 1 show, the majority of the respondents are from Universities and Research establishments, and only 11% are from a large number of construction sectors other than materials and equipment supplier (including: contracting, design, survey, service, project management, etc.). Some of the feedback appeared to suggest that the low rate of industrial response was mainly due to the very limited knowledge/awareness of nanotechnology development and a lack of interest in getting involved at this time among the construction firms.

It was found that the awareness of nano-related applications in construction was generally much higher among the academics/researchers than the industrial personnel. Understanding phenomena at nanoscale was the only activity/application in construction known to the majority of the industrial personnel responded. Furthermore, the areas of activities which the respondents were more aware of are those of the materials development and fundamental research nature.

The results of the survey of construction professionals and leading researchers on their involvement in nano-related research and applications in construction are presented in Tables 2 and 3 respectively.

The results in Table 2 appeared to show that understanding phenomena at nanoscale and nano particles, filler and admixtures were the two activities/applications in construction best known to the respondents. The awareness of nano-related activities was generally much higher among the academics/researchers than the industrial personnel. Furthermore, the areas of activities which the respondents were more aware of are those of the materials development and fundamental research nature.

The results in Table 3 seemed to be consistent with the findings of Table 2, *i.e.* the major activities of the respondents are in the areas of High performance structural materials and Understanding phenomena at nanoscale. It is noted that except for a limited involvement in the area of High performance structural materials, the industrial personnel have little involvement in nano-related activities.

Table 1 - Distribution of the survey respondents in various sectors related to construction

Core business sectors	Number of respondents	% of total respondents
University	28	34%
Research establishment	26	31%
Industry – materials and equipment supplier	15	18%
Industry – all sectors except the above	9	11%
Others not yet related to construction	5	6%

Table 2 - Awareness of nano-related applications in construction

Awareness of nano-related research and applications	% of those responded	
	Academics/ researchers	Industrial personnel
Understanding phenomena (*e.g.* cement hydration) at nanoscale	82	58
Nano particles, 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 3 - Involvement in nano-related activities by the respondents

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

Another important finding coming out of the survey was the perception/attitude of the construction industry on nanotechnology developments and potential applications in construction. All but two respondents agreed that the public was not properly informed, or was confused about nanotechnology in general, and the situation was among the worst in the construction industry. Particularly, as pointed out by some respondents, the information on nanotechnology applications is not always appreciated in the construction industry – a general attitude being 'wait and see'. Nanotechnology was, if anything, perceived as expensive and too complex to explain to clients who want a structure built as soon and as cheaply as possible.

This contrasts with the very rapid growth in awareness of and interest in nanotechnology development in many other industrial sectors, such as chemicals, automobiles and energy, etc.

In responding to the second stage of the survey, the selected 54 respondents provided information on their recent and existing research projects relevant to nanotechnology in construction. The results of the survey were surprisingly positive, as nearly 100 research projects (though some replicate) were identified as related to nanotechnology in construction among the respondents. A summary of the major research projects being carried out by the respondents is listed below:

- *High performance structural materials* – nanostructure modification of steel/metals, ceramics/glass, polymers, cement/concrete, composites through process control or using nanoparticles, nanotubes and nano-admixtures.
- *Understanding phenomena at nanoscale* – nano-structure and macro-properties relationship, (*e.g.* hydration, shrinkage, deterioration, etc.) using new techniques.
- *Functional thin films/coatings* – much enhanced performance in, *e.g.*, optical, thermal, durable, abrasion resistant, self-cleaning, anti-graffiti, etc.
- *New sensors, devices and smart structures* – enhanced monitoring of structural and environmental conditions, and self-actuating capability, though this tended to be at micro rather than macro-level.
- *Sustainable energy, environment applications* – new fuel cells, energy-efficient lightings, special insulating and glazing, pollutants cleaner, etc.

4.2 Existing activities of nanotechnology relevant to construction - desk study

As a result of the unprecedented funding in the area of nanoscale science and technology, interests and activities in nanotechnology R&D have been increasing substantially across industrial sectors. The R&D activity relevant to construction is not an exception.

In Europe, an analysis of expression of interests (EoI) submitted to the EC FP6 in 2002 found that there were 20 (out of a total of 250) EoIs related to nanotechnology application in construction. The EoIs covered a wide range of interests/activities, namely understanding and modelling of phenomena at nanoscale, developing nanoscale particles and fibres, nanostructure modified materials, functional materials, thin films and coatings/paints, energy efficient devices, and smart materials and integrated systems incorporating nano sensors/actuators.

In the USA, several research programmes directly linked or relevant to construction and the built environment have been funded under the NNI and by the National Science Foundation to study the fundamental aspects of materials, creation of new materials/functionality, deterioration science, sensing/diagnostic technologies, renewal engineering, multiscale modelling, simulation and design of materials, and construction automation, etc [21]. Some research and development activities aiming at commercial application/products based on nanotechnology are also evident, and mainly funded/conducted by start-ups and large industrial cooperation.

In Australia, the new Australian National Nanotechnology Network announced in 2002 its first collaborative effort – the Nano House Initiative. The initiative is aimed at creating an effective climate for the exploitation of new nanotechnological products/processes and teaching the wider public about what nanotechnology can offer. The "nano house" to be built will represent the current best practice in sustainable and environmentally friendly housing using the most recently developed nanotechnology-based materials and components. The initiative is an excellent vehicle for demonstrating applications of nanotechnology to public, and how these applications interact with each other and conventional materials, in order to stimulate the diffusion of nanotechnology into industries [22].

In Canada, an internal report of the Institute for Research in Construction (IRC), National Research Council Canada, has also recognised the importance and possible applications of nanotechnology to the construction industry [23]. More recently, IRC has initiated a multi-researcher project to develop new technologies and products for the construction industry based on nanotechnology, with an emphasis on cements, cement-based products, admixtures and concrete [24].

The rapidly increasing interest in nanotechnology is also evident in Japan, China and many other countries, and has been reflected in many new publications and reports.

The following areas have a significant potential for applications in construction and the built environment. Some of them are already being developed by industrial companies, and several products already have sales.

4.2.1 Nanoparticles, carbon nanotubes, nano-fibres, etc.

This area is perhaps the most commercially developed and the use of these nanoscale materials has been the basis for many current and potential applications in various industrial sectors. There have been a large number of companies producing many different types of nano particulate/fibre materials, such as carbon nanotubes, nanoclay, metallic and non-metallic oxides, etc. For the construction sector in particular, nanoparticles, carbon nanotubes and nano fibres offer a potential for developing much stronger, tougher and more durable structural materials, as well as new functional materials/coatings and devices/systems with much enhanced performance for use in construction and the built environment.

With particular relevance to construction and the built environment, several nanoparticulate materials (*e.g.* TiO_2, SiO_2, $CaCO_3$ and silicate clay) have been widely used as fillers/additives in coatings/paints, adhesives, sealants and composites. For example, nanoclay and nanotubes/fibres are increasingly used as reinforcement in high performance composites. Dispersion/slurry of amorphous nanosilica particles has also been produced as cement/concrete admixtures, which can be used to improve segregation resistance for fresh slurry and self-compacting concrete, or to enhance strength/durability performance of hardened concrete [25-27].

Nanoparticulate materials have shown significant potential in protecting the environment and enhancing sustainability. A variety of nanoparticles have been studied for use in chemical processing to reduce waste or replace toxic materials, and for treatment or remediation of pollutants in the environment. For example, TiO_2 nanoparticle-based coatings can capture and absorb organic and inorganic air pollutants by a photocatalytic process. Coating of 7000 m^2 of road surface with such a material in Milan in 2002 has led to a 60% reduction in nitrogen oxides concentration at street level [28]. Research has also demonstrated that bimetallic nanoparticles, such as Fe/Pd, Fe/Ag, or Zn/Pd, can serve as potent reductants and catalysts for a large variety of common environmental contaminants [29].

Advances in the field of nanotechnology have increasingly enabled development of 'internally engineered' materials by design and control/manipulation of their structure at the nanoscale - the molecular structure of materials is changed to suit the requirements. We know, for instance, that the molecular structure of carbon, when changed to a spherical geodesic form, becomes more fluid; and carbon nanotubes (CNT) thus developed show extraordinary properties (*e.g.* with elastic modulus and yield strength in axial direction being over 1 TPa and 60 GPa respectively and a yield strain in the order of 6%, as well as both conducting and controllable semi-conducting).

Attempts have also been made to use nanotubes, particularly carbon nanotubes (CNT), to reinforce polymer, metal, ceramics and cement-based matrix [30-33]. For example, 15% addition of CNTs by volume has been found to increase the electrical conductivity of alumina by 13 orders of magnitude [25]. A CNT composite has recently been reported to be six times stronger than conventional carbon fibre composites [13]. Additionally, unlike carbon fibres which fracture easily under compression, the nanotubes are much more flexible and can be compressed without fracturing.

4.2.2 Understanding phenomena of traditional construction materials at nanoscale

Initial efforts to exploit nanoscience/nanotechnology development in the construction sector have mainly focused on understanding phenomena and improving performance of existing materials/products. Work in this aspect remains to be one of the most active for nanotechnology-related research/activities in construction.

Traditional construction materials, such as concrete, asphalt, plastics and steel, are used on a large scale and produced in huge quantities. Historically, it has been possible to assess the properties of such materials only on macroscale. To give one example only, cementitious materials have existed for over 2000 years, and at present more than 2 tons of concrete per person on average are used annually around the world. Despite their undisputed importance, omnipresence and low-tech status, however, cement-based materials are among the least well-understood materials due to their complex nature. Particularly, structural concretes have composite structures with features spanning 10 orders of magnitude in dimension, ranging from nanometre-sized pores and C-S-H gel to steel reinforcement that can be tens of metres in length, to paste, sand and stone particles of all sizes in between. Such complex structures are made even more complicated by the time-dependent nature of the binding or cement hydration processes which start at the mixing of cement clinker minerals with water and continue for months and even years.

The performance/properties of concrete are strongly influenced by the main hydration product, C-S-H (calcium silicate hydrates) gel, that is a variable, nanoscale composite material itself, and significantly modified by a multi-scale (from nm to mm) network of capillary pores and microcracks. Therefore, fundamental understanding at the nanoscale of the development and behaviour of the cement matrix and its interaction with the other constituents and the environment can provide a systematic and cost effective means to develop superior concrete and to better control properties and degradation processes. Recent rapid progress and improved availability of advanced instruments and characterisation techniques sensitive to nanoscale structure and properties has led to an increasing number of research projects studying at micro/nano-scale the various structures, properties and underlying mechanisms of cement-based materials.

Another important approach in studying the multiscale structure-properties relationship is by means of modelling and simulation. Various studies based on micromechanical and numerical modelling/simulation techniques have been reported [34-36]. Furthermore, molecular dynamics modelling/simulation methods have recently been used to study the structures of various cement hydrates and the interactions of aqueous Cl^- with their surfaces [37].

Advances in development of design tools, by taking account of the properties of microstructural constituents of the composite material and making use of the modelling/simulation techniques, will allow structures to be built with smaller design margins. This progress, even if only slight improvements in the design, production processes and the materials' performance, can have enormous social and economic impact due to the multiplier-effect of the huge quantities of materials used.

4.2.3 Nanostructure modified bulk materials

The most significant current example is perhaps the nanostructure-modified steel reinforcement – MMFX2 Steel, manufactured by MMFX Steel Corp. USA [38]. The steel has a corrosion resistance similar to that of stainless steel, but at a much lower cost. Compared to conventional carbon steel, the MMFX steel has a completely different structure at nanoscale – a laminated lath structure resembling 'plywood' as shown in Fig. 2. Due to the modified nanostructure, MMFX steel also has superior mechanical properties, *e.g.* higher strength, ductility and fatigue resistance, over other high-strength steels. These material properties can lead to longer service life in corrosive environments and lower construction costs.

Since corrosion of steel is one of the most serious and costly problems facing construction today, the implications of highly corrosion resistant steel, such as MMFX 2, are far reaching. So far, the MMFX steel has gained essential qualification/certification for use in general construction throughout the US. It has attracted considerable interest from Federal Highway Administration, US Navy and Departments of Transport of various states. Projects using the MMFX steel are currently underway or in the federally funded submission stage in 22 states of the US. MMFX is also concentrating efforts on the approximately 12 million ton per year (North America) general construction reinforcing steel markets.

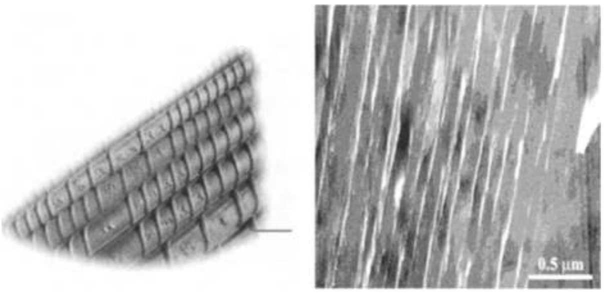


Fig. 2 - Nanostructure modified steel reinforcement – TEM picture showing microstructure of nano sheet of austenite in a carbide free lath of martensite (MMFX Steel Corp. USA [38]).

Another important area of development is in bulk insulating materials, such as bulk nanoporous silica compounds and aerogel. NanoPore has developed bulk nanoporous silica compounds with embedded organic molecules which perform up to 10 times better than conventional insulating materials [11, 39]. The superior insulation characteristics of these low-density, highly porous solids are due to the unique shape and small size (10-100 nm) of its large number of pores. So far, these new insulating compounds have been used in a wide variety of insulation applications that require excellent thermal performance, optimum energy efficiency, or minimum insulation thickness.

Several other nano-enabled high performance structural materials, such as high strength ductile cement/ceramics, glass, metal and polymer nanocomposites, which have been developed for automotive and military applications, also have the potential for construction applications. For example, hard and tough ceramics could be used as cutting tools, high strength springs and wear-resistant parts; and ductile cement, glass and polymer nanocomposites could be used in construction components for earthquake or impact resistant structures.

4.2.4 Functional coatings and thin films

Incorporating certain nanoparticles or nanolayers into coatings/thin films can provide enhanced performance and additional functionalities. Currently, several products have been developed and marketed for construction and the built environment, including: protective or anti-corrosion coatings for components; self-cleaning, thermal control, energy saving, anti-reflection coatings for glass/windows; easy-to-clean, anti-bacteria coatings for work surfaces; and more durable paints and anti-graffiti coating for buildings and structures.

For example, self-cleaning windows have been developed and marketed by Pilkington, St. Gobain Co., and others [40-41]. The special coating works in two stages. First, using a 'photocatalytic' process, nanosized TiO_2 particles in the coating react with ultra-violet rays from natural daylight to break down and disintegrate organic dirt. Secondly, the surface coating is hydrophilic, which lets rainwater spread evenly over the surface and 'sheet' down the glass to wash the loosened dirt away.

Another approach to create self-cleaning surface coating has been the development of 'Lotus Spray' products by BASF [42], based on ideas of replicating the spotless lotus leaves. The product offers 20 times more water-repellent property than a smooth, wax coating. With applications in the construction industry in mind, the company aims to develop a product that will retain its lotus effect even after an abrasion with sandpaper.

Special coatings developed can also make the applied surface both hydrophobic and aleophobic at the same time. These could be used for anti-graffiti surfaces, carpets and protective clothing, etc. Graffiti on buildings and structures is particularly a problem in large cities. For example, the cost of graffiti cleaning is estimated at $150m a year for Los Angles [43]. Researchers in Mexico has successfully developed a new type of anti-graffiti paint DELETUM, by functionalising nanoparticles and polymers to form a coating repellent to water and oil at the same time, as shown in Fig. 3. As a result, the coated surface is non-stick or very easy to clean, and able to withstand repeated graffiti attacks.

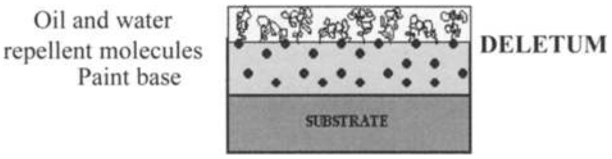


Fig. 3 - Stratigraphy of Deletum anti-graffiti coating [43].

Furthermore, nanostructured coatings can be used to selectively reflect and transmit light in different wavebands. These coatings can be used on windows as radiant heat reflectors, with many energy saving applications [44]. Research is also focusing on smart and responsive materials able to sense and adapt to their surroundings and change their appearance, such as architectural coatings whose colour changes as a function of temperature, and cladding which responds to heat and light to minimise energy use in buildings [45].

4.2.5 Environment and performance monitoring sensors and devices

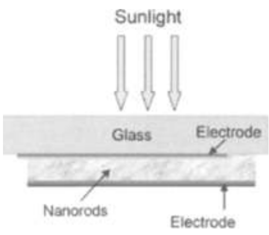
Microscale sensors and microscale sensor-based devices/systems have already been used in construction and the built environment to monitor and/or control the environment conditions (*e.g.* temperature, moisture, smoke, noise, etc.) and the materials/structure performance (*e.g.* stress, strain, vibration, cracking, etc.). Nanotechnology approaches are not only enabling devices to be made much smaller, more reliable and energy efficient, but also opening up new possibilities beyond the reach of mere micron-scale manufacture (*e.g.* biomimetic sensors and carbon nanotube systems).

Nanotechnology enabled sensors/devices also offer great potential for developing smart materials and structures which have 'self-sensing' and 'self-actuating' capability. The device used for air bags in cars is such an example. Cyrano Sciences has developed electronic noses based on an array of different polymer nanometre-thin film sensors [http://www.cyranosciences.com]. The devices, which are much more sensitive and cheaper to run than sniffer dogs, have been tried for applications in detection of harmful/poisoning gases, food quality, chemical leaks, pollution, contamination, and diseases. Siemens and Yorkshire Water are developing autonomous, disposable chips with built-in chemical sensors to monitor water quality and send pollution alerts by radio [46]. Other potential applications in construction may include building materials (*e.g.* concrete) with self-healing ability at cracking/damage, tools with embedded intelligence, and buildings/structures able to adapt to changing service and environment or weather conditions.

4.2.6 Energy performance, communication and other applications

Nanotechnology R&D is forming part of the quest to prevent/reverse environmental damage and to promote sustainable development. Progress in the areas of new environmentally friendly energy sources, energy efficient lighting and space conditioning devices/systems, and effective filters for water and air is likely to have significant impact on construction and the built environment.

The most promising application in the areas of energy and environment is the development of fuel cells and photovoltaics. In the last few years, considerable efforts have been made to develop plastic solar cells (*e.g.* Fig. 4),



Schematic diagram of a hybrid "plastic" solar cell with a nanorod/polymer layer sandwiched between two electrodes. The middle layer, a mere 200 nm thick, is a jumble of nanorods embedded in the semi-conducting polymer.

Fig. 4 - Cheap, plastic solar cell [47].

flexible enough to paint onto any surface, and much simpler and cheaper to produce than that of conventional silicon semiconductor solar cells [47].

Energy efficient lighting is another important area which will benefit from nanotechnology development. Light emitting diodes (LEDs) have been used widely in portable electronics and mobile phone displays. Continuing development in LED technology may provide the breakthrough required to produce light bulbs – next generation lighting that lasts for years and consumes less than half the energy of conventional lighting [48]. Replacing conventional lamps with LEDs in the United States alone could generate energy savings of up to $100 billion by 2025 and reduce carbon emissions by 200 million tons per year [48, 49].

With further development and applications of these technology/products and progress in the insulating materials and smart glazing, the vision for buildings to meet their own energy requirement will become a reality.

There are many other nanotechnology-enabled developments and materials/products fast emerging or already available in bulky and expensive forms in different industrial sectors. With the continuing reduction of size and affordability and improvement of performance, these products and developments are also likely to impact on the construction process and the built environment in the short to medium term. These may include ever-improving computers, electronic and communication devices/systems, tracking/tagging devices (*e.g.* based on GPS, Quantum dots, fluorescent nanoparticles, radio frequency ID, etc.), efficient and effective catalysts, and novel (*e.g.* biomimetic, self-assembly) materials, to name just a few.

4.2.7 Biomimetic, hybrid, self-assembly materials

One of the ultimate goals (and the most debated area) of nanotechnology is molecular manufacturing based on self-assembly or self-replicating nano machines (thus the vision of buildings that build themselves). Though increasing evidence indicates that molecular manufacturing is possible, full molecular nanotechnology capability is unlikely to be developed for at least 20 years [50]. However, extensive effort toward that goal, and particularly biomimetic study to better understand and replicate nature's version of molecular nanotechnology (*i.e.* the way living organisms produce food and materials) is being made and is likely to have huge potential for new materials and processes applicable to construction in the next 5-15 years.

In the fundamental level of understanding of living organisms, it has been known that biological cells have amazing materials properties, which are based on their macromolecular and supramolecular (or colloidal) building blocks [51]. All cells contain similar macromolecules but different types of cells can survive in very different environments. Indeed, cells can live in boiling water, in strong acids, at the low temperatures of the Antarctic, and under the enormous pressures of the deep sea. These different adaptations, which are based upon different supramolecular architectures/assemblies, demonstrate the wide range of possible material properties of these architectures [51].

Biomimetics is the science of mimicking nature, and biomimetic materials seek to replicate the best features of natural materials, whose structures have been fine-tuned over many million years' evolution. Examples of natural systems with desired properties are almost everywhere, such as honeycomb giving a lightweight structure with exceptional mechanical strength, antler bone being tougher than any man-made ceramic composites, lotus leaf giving self-cleaning surfaces, chameleon's skin changing colours with the environment, etc. With growing skills in seeing and manipulating materials at the atomic level enabled by nanotechnology advances, biomimetic materials research provides a productive approach to creation of new materials/products and molecular manufacturing.

An interesting example is mimicking geckos' hairy feet. Geckos are famed for their wall-climbing antics and their ability to hang from the ceiling or even polished glass by a single toe. They can do this because each of their toes contains half a million small hairs, and the end of each hair splits into 100 – 1000 tiny spatulas that bond with any surface through van der Waals (*i.e.* intermolecular) forces [52, 53]. The strong adhesion is also immediately reversible as, at a certain angle, the ends automatically detach and roll up. Inspired by gecko's hairy feet, researchers in the UK have produced a prototype super-sticky adhesive tape which is extremely strong, waterproof and reusable [53]. The tape is produced by fabricating arrays of plastic pillars/fibres about 2 μm tall and apart, on a flexible base that moves to bring the minute synthetic hairs into contact with all the small undulations on surfaces (Fig. 5).

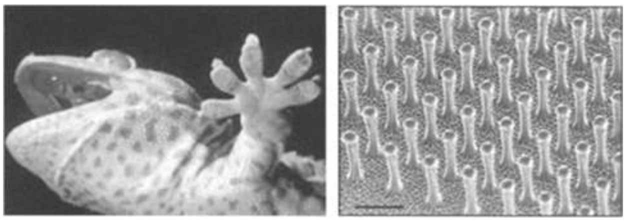


Fig. 5 - Super-strong, waterproof and reusable adhesive tape developed by copying gecko's hairy feet, picture on the right showing arrays of 2 μm tall synthetic hairs [52, 53].

Significant research is also being carried out to understand and emulate spider silk and its spinning technique [54, 55]. It has been found that spider's dragline silk has an extraordinary combination of toughness and strength. A dragline strand, being about one tenth the diameter of a human hair, is several times stronger than steel on a weight-for-weight basis, and can stretch great lengths without snapping (Fig. 6). The secret of dragline silk lies in its composite structure which is composed of two different proteins, each containing three types of regions with distinct properties. Apart from its superior mechanical properties over man-made fibres, spider silk can be spun in air or underwater (does not require high temperature/pressure or clean room facilities), and is also highly resistant to degradation [54].

Another essential feature of natural materials is their structural organisation of different types of building blocks at

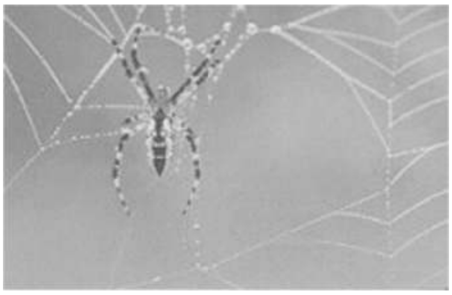


Fig. 6 - Secret of spider silk and its spinning technique [54].

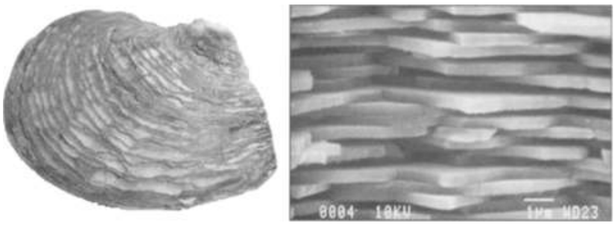


Fig. 7 - Abalone shell's extreme toughness comes from its micro-laminate composite structure made up of tiny calcium carbonate crystals and proteins [57].

many scales. A well-known example is the hierarchy 'bricks-and-mortar' composite structure found in seashells. As shown in Fig. 7, an abalone shell consists of layers roughly 0.2 mm thick, and each of these layers is a bricks-and-mortar assembly of yet more layers, each about a 0.5 μm thick [56-58]. Such a micro-laminate brick-mortar composite is made up of tiny calcium carbonate crystals bonded by only a few percent by mass organic glycoprotein. The result of the multiscale, hybrid structural organisation and the special characteristics of the organic glue is a composite material - shell that has fracture toughness 3000 times greater than that of the calcium carbonate crystal alone [58]. That is why cracks occurring on the outside few layers of the shell rarely make it all the way through. The cracking process takes a tortuous route along the glue layer, dissipating/absorbing large amounts of energy along the way. Current studies on seashells have moved a step further by examining the processes and mechanisms of the structure formation, which will likely lead to potential new manufacturing processes (*e.g.* self assembly) and controls.

5. FUTURE TRENDS AND POTENTIAL

The survey of construction professionals and the examination of current worldwide nanotechnology development relevant to construction applications appear to indicate that most of the research areas discussed above will have a significant impact on construction and the built environment within the next 10 years. The greatest impact to the construction industry and the economy within this time frame is likely to come from enhancement in performance of materials stemming from better understanding and control at the nanoscale and improvement of production processes, due to the huge quantities of materials involved. The advances are likely to be incremental on existing materials and technologies.

In the medium to long-term (*i.e.* > 10-15 years), major breakthroughs in materials science are expected. Such breakthroughs will enable the 'materials by design' approach to replace the traditional 'trial and error' one to tailor a material for a specific requirement. It will also lead to development of more sophisticated, simulation-based design tools, new approaches to extend the life of existing structures and to prevent deterioration in the new build.

Furthermore, nanotechnology development, particularly in conjunction with biomimetics research to uncover secrets of natural materials' structure formation and manufacturing process will lead to truly revolutionary approaches to design and production of materials and structures with much improved energy efficiency, sustainability and adaptability to changing environment.

Ultimately, work on molecular nanotechnology offers the promise that building builds itself (*i.e.* getting molecules to do the work).

6. CONCLUSIONS

The results of the survey and the desk study appear to indicate that nanotechnology R&D in the broad area of construction and the built environment lags behind other industrial sectors, and has been driven largely by governments, foresight institutes and academics/researchers working in the field.

Nanotechnology application in construction is still a very small, fragmented pursuit and unknown outside the scientific circle. However, limited commercial activities have started to emerge and some nano-based materials/ products are now used or ready to be adopted by the industry, and many others are coming to the market. New products/processes are developed to fulfil a need and although this may not be specifically for construction, there are many opportunities for transferring technology.

There appears to be a lack of awareness and negative perceptions of nanotechnology among construction professionals. To rectify this negativity, integrated actions are needed for targeted R&D, for technology watch and knowledge transfer in construction industry.

Huge potential has been predicted for nanotechnology applications in construction, and even minor improvements in materials and processes could bring large accumulated benefits. In the short to medium term, the greatest impact to the construction industry and the economy is likely to come from enhancement in performance of materials. In the medium to long term, nanotechnology development will lead to truly revolutionary approaches to design and production of materials/structures with much improved energy efficiency, sustainability and adaptability to changing environment.

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