

Nanotechnology Innovations for the Sustainable Buildings of the Future

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Abstract—Sustainability, being the urgent issue of our time, is closely related with the innovations in technology. Nanotechnology (NT), although not a new science, can be regarded relatively a new science for buildings with brand new materials and applications. This paper tends to give a research review of current and near future applications of nanotechnology (NT) for achieving high-performance and healthy buildings for a sustainable future. In the introduction, the driving forces for the sustainability of construction industry are explained. Then, the term NT is defined, and significance of innovations in NT for a sustainable construction industry is revealed. After presenting the application areas of NT and nanomaterials for buildings with a number of cases, challenges in the adoption of this technology are put forward, and finally the impacts of nanoparticles and nanomaterials on human health and environment are discussed.

Keywords—Nanomaterial, self-healing concrete, self-cleaning sensor, nano sensor, steel, wood, aerogel, flexible solar panel.

I. INTRODUCTION

CONSTRUCTION industry is the largest single contributor to the environmental problems, with the construction, operation and maintenance of buildings, thus making the high-performance, green building movement the most successful attempt for the sustainability of our planet. Both the existing built environment and the process of adding to it, have numerous environmental, social, and economical impacts [1]. Worldwide buildings are estimated to account for 50 % of all energy consumption, and more than 50 % of global emissions, [2], as well as consuming between 30 and 40 % of the global electric energy [3]. Environmental pollution, deforestation, soil erosion, ozone depletion, fossil fuel depletion, and human health risks are the significant consequences of design, construction and operation of buildings, which disregard the impacts on the environment. Clearly, construction activities play the most significant role in our current environmental predicament.

According to Zimmermann [4], there are 24 problematic emissions that result from buildings during their lifecycle, and two of them are very significant; sulphur dioxide, resulting from energy generating from fossil fuels; and fine particulates due to extracting mineral raw materials for construction. European Union [5] also mentions the general aspects of construction impact on the environment as follows:

- a) Emissions into the air,
- b) Releases to water,
- c) Avoidance, recycling, reuse, transportation and disposal of solid and other wastes, particularly hazardous wastes,
- d) Use and contamination of land,
- e) Use of natural resources and raw materials,
- f) Local issues (noise, vibration, odour, dust, visual appearance, etc.),
- g) Transportation problems,
- h) Risks of environmental accidents and effects arising, as consequences of incidents, accidents and potential emergency situations,
- i) Effects on biodiversity of atmospheric emissions.

In addition, compared with other industries, the construction industry presents an unusual case that it is long lasting. Much of the built environment of our time will exist in the future, which will be the era of rising temperatures and sea levels. Structures in developed countries have an average life of 80–100 years. In many countries there are buildings, bridges and other structures hundreds of years old. This means that the design of a building will have long-term repercussions on a structure's environmental performance. To accomplish high-performance, low-environmental-impact buildings, it is vital to incorporate sustainability principles by the initial phase of a project, through the lifecycle as well [1].

The term sustainable (or high performance/green) building is often used to comprehensively address the ecological, social and environmental problems in the context of its community. In 1994, the Conseil International du Batiment (CIB) defined the goal of sustainable construction as "...creating and operating a healthy built environment based on resource efficiency and ecological design" [6]. The CIB also defined seven principles for a sustainable construction industry, which would help decision-making during the design and construction phases that will also impact through the life cycle of the building (Table I).

TABLE I
THE PRINCIPLES OF SUSTAINABLE CONSTRUCTION [6]

1	Reduce resource consumption	(reduce)
2	Reuse resources	(reuse)
3	Use recyclable resources	(recycle)
4	Protect nature	(nature)
5	Eliminate toxics	(toxics)
6	Apply life-cycle costing	(economics)
7	Focus on quality	(quality)

As seen from the Table I, the term *sustainable construction* is closely related with construction materials, how they are

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extracted from the nature, manipulated, manufactured, used in buildings and destroyed, as well. At least 3 billion tones of materials are used in buildings each year, which is equivalent to about 40% of total global material flows and building material waste is estimated to be about 2 billion tones per year [7]. In this context, the potential for resource and energy conservation, as well as reduction of non-renewable resource consumption, waste, toxicity, and carbon emissions through architectural applications of new and innovative technologies is significant. The shift from traditional to high-performance and state-of-the-art applications of buildings will be possible through innovations in structural materials, insulation, coatings, adhesives, air and water purification, as well as solar technologies. The foremost of these innovative technologies is the nanotechnology and nano-enhanced materials, whose market applications have already, began with small consumer devices.

This paper tends to give a research review of current and near future applications of nanotechnology (NT) for achieving high-performance and healthy buildings for a sustainable future. Initially the term NT is defined, and significance of this technology for a sustainable construction industry is explained. Then application areas of NT and nanomaterials for buildings are presented with a number of examples, and finally challenges in the adoption of this technology, as well as impacts on human health and environment are discussed.

II. NANOTECHNOLOGY

NT is a field that is dominated by developments in basic physics and chemistry research. By the advent of NT, the use of very small particles of material, either by themselves or by their manipulation to create new large-scale materials, is possible. NT is not a new science or a new technology; it is rather an extension of the sciences and technologies that have already been in development for many years. It was initially introduced in the speech of the physicist R. P. Feynmann during his lecture entitled "*There is Plenty of Room at the Bottom*", that took place in a meeting of the American Physical Society in 1959 [8]. Feynmann described a process by which the ability to manipulate individual atoms and molecules might be developed, using one set of precise tools to build and operate another proportionally smaller set, and so on down to the needed scale.

There have been many revolutionary developments in physics, chemistry and biology, which have demonstrated the idea of manipulating matter at an extremely small scale. Another definition of NT was also presented in 1981 by K. Drexler, as being the production with dimensions between 0, 1 and 100 nm [9]. As a comparison, a human hair has 80,000 nm thickness and the DNA double helix has 2 nm diameter [10]. The key in NT is the size of particles, since the material properties are dramatically affected under a scale of nanometer (10^{-9} meter). As particles become so small, the proportion of atoms on the surface increases relative to those inside and this leads to novel properties. Gravity becomes unimportant, quantum physics principles apply on, and electrostatic forces take over. Related with construction,

concrete becomes more durable and stronger, steel tougher, glass surface self-cleaning, thus all these innovations contributing to a more efficient use of natural resources and healthy environment.

Although the meaning of NT varies from field to field, it is broadly defined as the understanding, controlling and restructuring of matter on the level of nanometers in order to create materials of new properties and functions [11]. It specifically implies not only the miniaturization, but also the precise manipulation of the atoms and molecules to design and control the properties of nanomaterials and nanosystems. These properties are completely different than those possessed by the bulk materials, producing custom-made devices with capabilities not found in bulk materials or in nature, or even to replicate natural processes that have not been currently achieved through synthetic materials.

One of the most noteworthy features of NT is that it replicates the natural systems, which have exceptional performance and also biodegradable, having no impact on the environment [10]. For instance, the abalone shells (Fig. 1) are made with 0.2 mm thickness layers, and each is made by a "mortar" 0.5 μ m thickness of calcium carbonate crystals bound altogether with a protein. The final result is a composite material with a toughness 3000 times the toughness of the calcium carbonate crystals [11], [12]. Another example is the coral reef, formed by the natural system using seawater in order to produce calcium, magnesium and carbonate to generate a carbonate crystal (aragonite). The spider silk is also another interesting example.

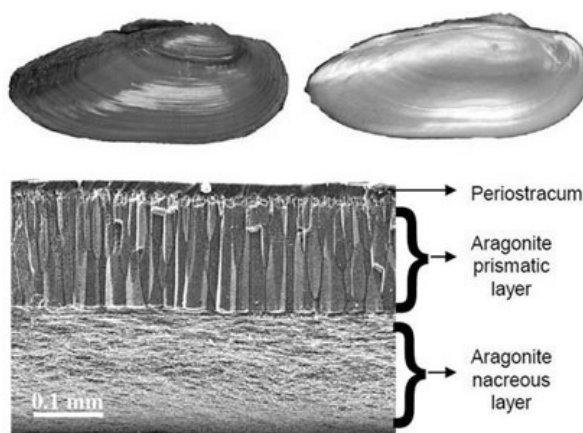


Fig. 1 The microstructure of the abalone shell

Nanoscale science can be divided into three main areas, as; nanostructures, nanofabrication and nanocharacterization with typical applications in nanoelectronics, energy and life sciences [13]. It also encompasses two main approaches (Fig. 2) [14]:

- i. The "top-down" approach, in which larger structures are reduced in size to the nanoscale while maintaining their original properties without atomic-level control (i.e., miniaturization of electronic equipments);

- ii. The “bottom-up” approach, also called “molecular manufacturing”, introduced by Drexler et al. [15], in which materials are engineered from atoms or molecular components through a process of assembly or self-assembly.

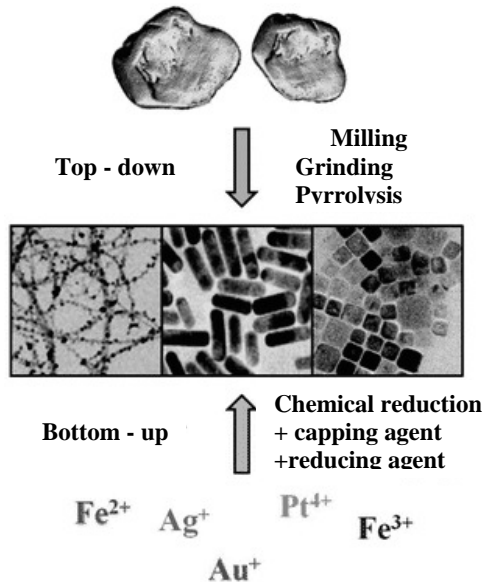


Fig. 2 Top-down and bottom-up approach in NT

While most of the innovations depending on NT rely on “top-down” approach, molecular NT is widely applied in materials and manufacturing, electronics, medicine, healthcare, energy, biotechnology, and information technologies as well. NT offers new opportunities in many industries based on cost-effective economies, thus contributing to a sustainable development. Related with global energy consumption, it has the potential to significantly reduce the impact of energy production, storage and use. When construction industry and buildings come to term, new structural materials, which are durable, stronger and lighter, fire insulator, coatings, water repellents, self-cleaning surfaces, air cleaners, nano-sized sensors, and etc. present new opportunities. In the following section, the application areas of NT, either in materials or in structures, are briefly presented.

III. SIGNIFICANCE OF NANOTECHNOLOGY IN CONSTRUCTION INDUSTRY

Application and significance of NT in construction industry and building materials have not been identified clearly until a recent date [16]. The first document, which clearly mentions the potential of NT in construction industry, is the report of RILEM TC 197-NCM by Zhu, et al. [17]. According to this report, the potential applications of NT in construction industry can be stated as follows:

- The use of nanoparticles, carbon nanotubes and nanofibers to increase the strength and durability of construction materials and components, as well as for pollution reduction,

- Affordable production of corrosion-free steel,
- Production of high-performance thermal insulation materials,
- Production of coats and thin films with self-cleansing and color-changing ability to minimize pollution and energy consumption,
- Production of sensors and materials of nano-size with sensing and self-repairing ability for more reliable structures.

Knowledge and manipulation of materials and structures at nanoscale promotes the development of new applications and new products to repair or improve the properties of construction materials. For example, the fundamental calcium-silicate-hydrate gel, which is responsible for the mechanical and physical properties of cement, shrinkage, creep, porosity, permeability and elasticity, can be modified to obtain better durability. When elements can be manipulated in nanoscale, macro-properties can be designed and new materials as well as processes can be designed [18]. The new characteristics of these new nanomaterials, which are maintained by the advent of NT can significantly fix current construction problems, and may change the requirement and organization of construction process.

For architects, engineers, developers, manufacturers, and building owners, NT and nano products offer extraordinary environmental benefits to help meet the rapidly growing demand for more sustainable buildings. In the following section the current and potential use of NT in the field of construction and building materials is reviewed. A variety of beneficial applications that encompass superior structural properties, functional paints and coatings, high-performance isolations, high-resolution sensing and actuating devices can be encountered. In this study, the categorization is made according to the application areas, rather than nanomaterial/nanoparticle types, such as carbon nanotubes (CNT), metal oxide nanoparticles (SiO_2 , Fe_2O_3 , TiO_2), and metal nanoparticles, which can be found in a number of other literature [17], [19]-[22].

IV. APPLICATIONS OF NANOTECHNOLOGY IN CONSTRUCTION INDUSTRY

A. Structural Materials

Structural materials are of utmost importance in a building, since they determine the durability, longevity and thus sustainability of the structure. A structural material's strength/weight ratio is also important, because stronger and lighter materials can carry greater loads per unit of material [23]. NT has the potential to improve structural materials in two ways; (i) by reinforcing of existing materials, such as concrete and steel, with the addition of nanoparticles in order to improve the properties of bulk material; (ii) by providing all of the structure constructed mainly by new materials, like carbon nanotubes (CNTs), when technically and economically feasible.

Concrete, having the largest annual production among other materials is one of the structural materials, which is

undergoing drastic enhancements by the advent of NT. Energy consumption, carbon emissions and waste are major environmental concerns related with concrete production and use. Portland cement, binding aggregate, water and lime, accounts for about 12 % of concrete's volume, but 92 % of its energy demand. For every ton of cement production, 1.3 tons of CO₂ is released into the atmosphere. Worldwide, cement production generates over 1.6 billion tons of carbon, more than 8 % of total carbon emissions. Waste is also considerable, as concrete accounts for more than two-thirds of construction and demolition waste with only 5 % currently recycled [23].

Conventional utilization of concrete must be reinforced with steel bars to resist tension, making it a timely and expensive process. However nanofiber reinforcement has been shown to improve the strength of concrete significantly. Also grinding Portland cement into nanoparticles has been proved to increase compressive strength up to four times [24]. Sanchez and Sobolev also made experiments by adding randomly oriented fibers ranging from nanometers to micrometers in length and made of carbon, steel or polymers, and they suggested the utilization of carbon nanofibers for concrete bridges, heating them in the winter or allowing them to self-monitor for cracks, since fibers have the ability to conduct electricity [14]-[25].

NT has a great potential to produce new cements and admixtures in order to achieve high-performance and sustainable concrete products. By the addition of CNTs and nanoparticles (SiO₂, Fe₂O₃) to the concrete mixture consisting of binding phase and aggregates, the mechanical properties of concrete elements can be improved. CNTs, which was first discovered in 1952 in Russia (and mostly ignored) and then re-discovered in the 1990's in Japan, are currently on a research phase of investigation. Adding 1% CNTs by weight improves the mechanical properties of concrete elements with mixtures consisting of Portland cement. CNTs also have the potential to effectively hinder crack propagation in cement composites. When cracks form in self-healing concrete, embedded microcapsules rupture and release a healing agent into the damaged region through capillary action (Fig. 3). This agent contacts an embedded catalyst, polymerizing to bond the crack face closed. This characteristic has the potential to increase the life of the structural components as much as two or three times [26].

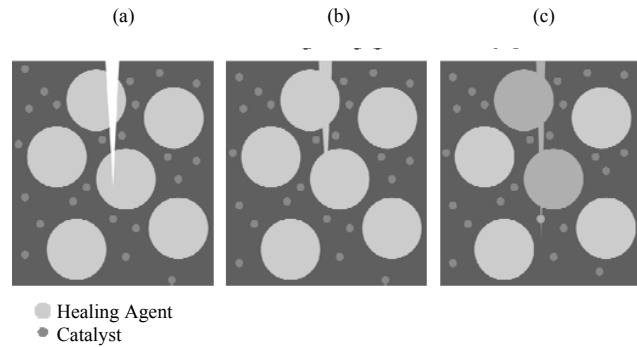


Fig. 3 Self healing matrix of concrete; (a) Crack forms in material; (b) Crack fills bursts microcapsule, releasing healing agent; (c) Contact with catalyst causes polymerization

Adding fly ash as an admixture to the cement not only improves concrete durability and strength, also reduces the requirement for cement contributing to sustainability. However, the curing process of concrete is slowed by the addition of fly ash and early stage strength is also low in comparison to normal concrete. With the addition of SiO₂ (silica) nanoparticles, part of the cement is replaced but the density and strength of the fly-ash concrete improves particularly in the early stages. Porro et al. also mention that the use of SiO₂ particles increases the compression strength of cement pastes, and this not due to pozzolonic reaction, because calcium hydroxide consumption was very low, but, to the increased silica compounds that contributes to a denser microstructure [27]. According to Lin et al., the use of SiO₂ nanoparticles on fly ash mortars, compensate the negative effects on initial strength [28]. Sanchez and Sobolev also report that SiO₂ nanoparticles addition leads to an increase of strength by 15-20 % [14].

Concrete is attacked by carbon dioxide and chloride ions, resulting in corrosion of the steel bars. Nanosensors have been designed and created for the reinforced concrete components of a structure to monitor and determine acidity and chloride ions, which are the primary reasons for deterioration and failure by the corrosion. These nanosensors can be embedded in the concrete mixture to enable, quality control and durability monitoring where these can be designed to (i) measure concrete density and viscosity, (ii) monitor concrete curing and measure shrinkage and (iii) measure certain key parameters affecting the durability of these structures such as temperature, moisture, chlorine concentration, acidity, carbon dioxide, stresses, reinforcement corrosion and vibration.

Self-Compacting Concrete (SCC) is another innovative structural material by the advent of NT, and does not need vibration in order to level off and consolidate. This significantly reduces the energy needed to build concrete structures thus making this material sustainable. In addition SCC can offer benefits of up to 50% in labour costs, due to it being poured up to 80% faster and having reduced wear and tear on formwork. The material behaves like a thick fluid and is made possible by the use of polycarboxylates. In addition,

while long-term strengths of conventionally superplasticized concrete are very high, the very early strengths, especially in winter, are not high enough for a quick and safe removal of formwork and steam curing is therefore used to accelerate the hydration of cement. This can be eliminated in the precast industry through the use of the latest generations of polycarboxylates resulting in further time and energy savings.

Steel, being a major component of reinforced concrete structures, as well as a primary construction material, is another material benefiting from innovations in NT. Steel has been widely available since the 2nd Industrial Revolution and has played a major role in the construction industry, which can today benefit from the application of NT. Actually, NT is not new for steel. Researchers recently discovered that Damascus swords, made in the 8th century and known for their unusual hardness and sharpness, incorporated naturally occurring nanoparticles including iron carbide nanowires and CNTs into their structure [29].

Corrosion resistance is very important in steel structures, as well as steel reinforcing bars in concrete structures. Today there are several forms of steel incorporating NT innovations. Two of these new products are now marketed as MMFX and MMFX2 steel. MMFX steel is five times more corrosion-resistant and up to three times stronger than conventional steel. MMFX steel products are used in structures across North America including bridges, highways, parking structures, and residential and commercial high-rise buildings. The added strength of MMFX steel results in a decrease in the amount of conventional steel necessary to accomplish the same task [30]. Although both products have corrosion resistance, have different mechanical properties and are the result of different applications of nanotechnology [20].

High-rise structures require high-strength joints necessitating high-strength bolts. The capacity of high-strength bolts is realized generally through quenching and tempering and the microstructures of such products consist of tempered martensite. By the addition of vanadium and molybdenum nanoparticles, the steel microstructure of the bolts can be improved and thus increasing their strength.

Although CNTs are an innovative and exciting material with tremendous properties of strength and stiffness, due to their graphitic nature, they have found little application as an addition to steel as their inherent slipperiness, thus making them difficult to bind to the bulk material and they pull out easily, rendering them ineffective. In addition, the high temperatures involved in steel manufacture and the effects of this on CNTs presents a challenge for their effective use as a composite component.

Wood is another structural material, which has been used since the ancient times. Two basic strategies incorporate NT into wood and wood-based materials. The first strategy uses nanomaterials and nanosensors developed in other industries and adapts them to the forest products, thus improving existing product performance. These products range from sheeting and siding with barrier coatings for water resistance, to high-performance composites of wood and wood fiber. The second strategy is to exploit the nanoscale properties of wood

to develop completely a new material, thus introducing light weight, economical, multifunctional, biobased one, competing with steel, concrete and other. Although CNTs are a new discovery of our time, wood, as a very old structural material, is composed of nanotubes or nanofibrils, that have approximately 25 % the strength of CNTs, and twice as strong as steel. If these cellulose nanofibrils could be extracted from wood, it would be cheaper than manufacturing carbon nanotubes [31]. Wood-based construction materials function extremely well under a variety of end-use conditions. However, they can be prone to decay, mold, and insect attack under wet conditions. Wood can be protected from deterioration by treatments using toxic chemicals or by maintaining low moisture content in wood. Achieving control of moisture is a major opportunity for NT. New non- or low-toxicity nanomaterials such as ZiO_2 , silver, TiO_2 nanoparticles and even clays might be used as either preservative treatments or moisture barriers. In addition, resistance to fire might be enhanced by use of nanodimensional materials like TiO_2 dioxide and clays.

Some developers have speculated that building functionality onto lignocellulosic surfaces at the nanoscale could open new opportunities for such things as self-sterilizing surfaces, internal self-repair, and electronic lignocellulosic devices. These non-obtrusive active or passive nanoscale sensors would provide feedback on product performance and environmental conditions during service by monitoring structural loads, temperatures, moisture content, decay fungi, heat losses or gains, and loss of conditioned air. Currently, however, research in these areas appears limited [20].

NT is foreseen as a cornerstone for advancing the biomass-based renewable, sustainable economy. Nanocatalysts that induce chemical reactions and make wood even more multifunctional than it is today, nanosensors to identify mold, decay, and termites, quantum dot fiber tagging, natural nanoparticle pesticides and repellents, self-cleaning wood surfaces, and photocatalytic degradation of pollutants are all envisioned by today's wood engineers [32]. In the broader sense, NT represents a major opportunity for the wood industry to develop new products, substantially reduce processing costs, and open new markets for bio-based materials.

B. Non-Structural Materials

Glass is one of the non-structural materials inevitably used in buildings, and the sustainability of the buildings is largely affected by the properties of glass as a glazing material, since it forms the most of the barrier between outside and inside, impacting the indoor air quality. Most of the heat gain and loss occurs on the glass surface, as well as impacting the level of daylighting. NT helps to improve the properties of glazing, especially the heat gain and loss, by thin-film coatings, thermochromic, photochromic and electrochromic technologies. Thin film coatings are spectrally sensitive surface applications for window glass. They filter out infrared light to reduce heat gain in buildings. Thermochromic glass, for instance, change transparency in response to temperature

and it is very useful to control overheating for passive solar heating applications. The temperature of the glass, which is a function of solar intensity and outdoor and indoor temperature, would regulate the amount of sunlight reaching the thermal storage element. Thermochromic glass would be particularly appropriate for skylights because the obscured state would not interfere with views as much as with a typical window glass. A thermochromic window can also be activated by a heating element in the window, making it operate like other switchable glazings, but this tends to be less energy efficient.

Photochromic glass, another sensitive glass, changes its transparency in response to light intensity. It has been used in eye-glasses that change from clear in the dim indoor light to dark in the bright outdoors. Photochromics may be useful in conjunction with daylighting, allowing just enough light through for lighting purposes, while cutting out excess sunlight that creates glare and overloads the cooling system [33].

The most promising adaptable glass technology, improved by the advent of NT is the electrochromic glass, which is composed of a five-layer coating about one micron thick, and is deposited on a glass substrate. The electrochromic stack consists of thin metallic coatings of nickel or tungsten oxide sandwiched between two transparent electrical conductors. When a voltage is applied between the transparent electrical conductors, a distributed electrical field is set up. This field moves various coloration ions reversibly between the ion storage film through the ion conductor and into the electrochromic film. The main advantages of this glass are that it requires low-voltage power, remain transparent across its switching range, and can be modulated to any intermediate state between clear and fully colored.

All these applications are intended to reduce energy use in cooling buildings and could help bring down energy consumption in buildings [20].

Plastics, which are another group of non-structural materials, are widely used in construction industry, especially for finishings. Polyvinyl chloride (PVC), which is used in door, windows, flooring, and etc., are mostly sensitive to fire and have been cited to have health effects on people because of the phthalates, used for flexibility of PVC components. New alternatives to many conventional plastics will be available in the market by the advent of NT researches. Naturally occurring nanoscale aggregates can also be used in making nanocomposites. The crystalline structure of these ceramic materials allows them to be easily separated into flakes or fibers. Nano-reinforced polyester provides excellent thermal and electrical insulation, while remaining strong and lightweight. The material is corrosion resistant, has a high fatigue limit, good impact strength, and fine surface finish. It can also be used as a load-bearing structural material and has been used in bridges, doors, windows, facades, and structural systems [34].

C. Nanomaterials for Insulation

An important aspect of sustainability in buildings is the efficient use of energy, and this can be achieved in passive

means by efficient insulation methods and materials. In the EU, over 40% of total energy produced is consumed by buildings, and households are responsible for one quarter of EU carbon emissions, roughly 70% of which comes from meeting space heating needs [23].

By the innovations in NT, insulation materials and applications will be more efficient and less reliant on non-renewable resources. Manufacturers estimate that insulating materials derived from NT are roughly 30 % more efficient than conventional materials [35]. Nanomaterials or nanoparticles can be applied to substrates using chemical vapor deposition, dip, meniscus, spray, and plasma coating to create a layer bound to the base material. These materials have the ability to trap still air within them, thus increasing their surface-to-volume ratio. These nanoscale insulation materials may be sandwiched between rigid panels, applied as thin films, or painted on as coatings.

One of the unique insulation materials developed by the advent of NT is the *Aerogel*, which is a highly porous solid material with extremely low density with large, open pores, and highly specific surface area (Fig. 4). This material, nicknamed “frozen smoke” is a gel in which liquid component has been replaced with gas. Despite its lightness, it can support over 2000 times its own weight. Its unique physical properties result with low thermal conductivity and low sound velocity, as well as high transparency. Since nanoporous aerogels can be sensitive to moisture, they are often marketed sandwiched between wall panels that repel moisture. Architectural applications of aerogel include windows, skylights, and translucent wall panels.

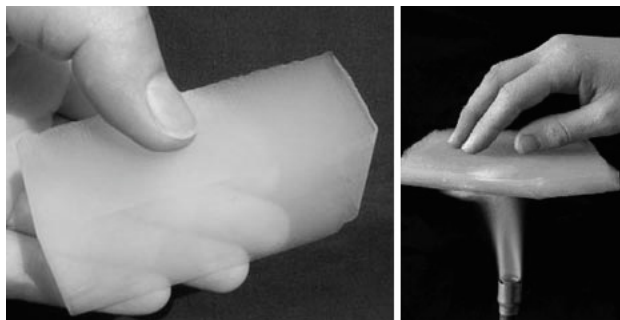


Fig. 4 Aerogel as an high-performance insulation nanomaterial

Nanocoatings can also be manufactured as *thin films*, and applied on glass and fabrics. For example fiber sheets, coated with stainless steel films can absorb infrared rays and blocks out sunlight, thus lowering room temperatures in summer by 2-3°C or more than conventional products [36]. Heat absorbing films can be applied to windows, offering cost effective control of heat and energy loads in buildings and solar performance. These thin film coatings utilizing SiO₂ and TiO₂ nanorods can control exterior reflectivity. These coatings have the lowest reflectivity ever reported [37].

Insulation can also be applied as a painting or spraying in the form of a coating, thus having tremendous advantages when compared with the conventional bulk insulators, such as

fiberglass, cellulose, and polystyrene boards, which often necessitates the removal of building envelop for installation. Insulation nanocoatings trap air at the molecular level, thus increasing their performance dramatically.

D. Coatings for Other Tasks

Besides the nanomaterials used for insulation, some others are developed to be used as coatings for other tasks, such as self-cleaning, depolluting, scratch-resistance, anti-icing/anti-fogging, antimicrobial, UV protection, corrosion-resistance and waterproofing.

Self-cleaning surfaces, which were the first architectural applications of NT, can be achieved by photocatalytic coatings containing TiO_2 nanoparticles, which initiates photocatalysis process by breaking down dirt by exposure to sun's UV rays. Volatile Organic Compounds (VOCs) are oxidized into carbon dioxide and water, then washed away by rain. These surfaces are made by applying thin nanocoating films, painting a nanocoating on or integrating nanoparticles into the surface layer of the substrate, such as concrete walls. Jubilee Church in Rome by Richard Meier and Partners, the Marunouchi Building in Tokyo, and the 40 Bond Street Apartment by Herzog & de Meuron in London are the remarkable examples, which utilize the state-of-the-art technology in self-cleaning façade systems (Figs. 5-7).



Fig. 5 Jubilee Church in Rome



Fig. 6 Marunouchi Building in Tokyo



Fig. 7 The 40 Bond Street in London

Self-cleaning surfaces offer energy savings by reducing the energy consumed in cleaning building facades, as well as depolluting and removing organic and inorganic air pollutants like nitrogen oxide from the air and breaking them down into relatively benign elements. Depolluting nanocoatings show considerable promise in cleansing indoor air and reducing instances of sick building syndrome (SBS). The World Health Organization (WHO) estimates that up to 30 % of new or renovated energy-efficient buildings may suffer from SBS [38]. A drawback of self-cleaning coatings is that they require sunlight for activation, reducing their effectiveness indoors. As an alternative for indoor applications, coatings using layered double metal hydroxides, air-cleaning nanocrystals, can be applied to indoor surfaces to improve the indoor climate and reduce ventilation requirements, thereby improving the building's energy efficiency [39].

Researchers at Yale University have also found that CNTs can kill *E. coli* bacteria. In their experiments, roughly 80 % of these bacteria were killed after one hour of exposure. According to the researchers, CNTs could be incorporated during the manufacturing process or applied to existing surfaces to keep them microbe-free. However, since CNTs can kill bacteria, they could have a major impact on ecosystems, so the EPA now regulates nanoproducts sold as germ killing, believing that they may pose unanticipated environmental risks [40].

E. Solar Energy Applications and Energy Storage

Utilizing solar energy as a renewable source, is one of the main approaches to achieve a sustainable building. In fact, sun is the primary source of the energies and other raw materials on the Planet Earth and it offers the cheapest and cleanest source, when utilized efficiently and economically. Current silicon-based solar cell technologies, however, have only achieved modest conversion efficiencies at relatively high costs. But technologies utilized for the conversion of sunlight to electric energy are improving, and the total market is growing rapidly.

NT offers innovative solutions to the expense of current silicon-based solar energy. For example, a company has developed a technology that has the potential to greatly reduce the cost of silicon-based solar cells. They have developed a silicon nanocrystalline ink that could make flexible solar panels as much as ten times cheaper than current solutions

(Fig. 8). Their silicon process lends itself to low cost and high efficiency [41].

While NT is leading to advances in silicon-based solar energy, it also supports silicon wafer technology as the primary technology behind solar cells with new nanocrystalline materials, thin-film materials, and conducting polymeric films. Revolutionary thin-film and organic solar cells are now entering the market and are expected to be significantly less expensive than current silicon-based solar cells. Organic thin-film, or plastic solar cells, use low-cost materials primarily based on nanoparticles and polymers. An advantage of organic thin films is their flexibility, which will enable their integration into building applications than conventional flat glass panels. This will open new possibilities and overcome the aesthetic problems that architects have with rigid flat panels, which can hardly be integrated into building facades.



Fig. 8 Flexible solar panels for energy generation used in buildings

Storing the energy produced from sun is also an important issue of the future and improvements in this area with the help of NT can reduce the dependence on fossil fuels, contributing to the sustainability of buildings. Currently, energy for homes and offices is not stored onsite. NT's possible contributions to the future of energy storage include improved efficiency for conventional rechargeable batteries, new supercapacitors, advances in thermovoltaics for turning waste heat into electricity, improved materials for storing hydrogen, and more efficient hydrocarbon based fuel cells [42].

F. Nano Sensors for Structural Applications

Monitoring the environmental conditions and controlling the material and component performance in contemporary structures are a current topic of research in our time. In reinforced concrete structures, for instance, concrete strength and durability largely depends on the temperature and the moisture transport within the components. Temperature and high moisture content can promote deterioration process, and jeopardize the integrity and long-term durability. The monitoring of temperature and moisture level provides crucial information about the hardening and setting process of Portland cement concrete as well as the progress of deterioration mechanisms such as corrosion of steel barst, freeze-thaw cycles, carbonation and alkali-aggregate reaction.

A new technique proposed by Norris et al. monitors the moisture level and temperature by the utilization of nanotechnology/microelectromechanical systems sensors (MEMs) to measure temperature and internal relative humidity [43]. One advantage of these sensors is their nano scale dimensions (10^{-9} m to 10^{-5} m), enabling them to be embedded into the structural components during the construction process (Fig. 9). These MEMs successfully monitor the behaviour of concrete at early age of measuring the temperature and internal humidity during the hydration process. However, more tests are required to evaluate the effect of different concrete mixtures on the MEMs response.

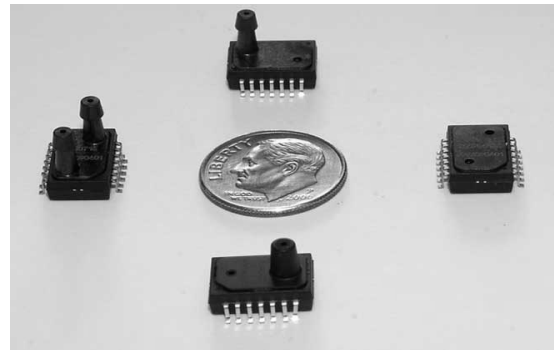


Fig. 9 Nano sensors embedded in concrete components

Smart aggregate, another sensing device of a low cost, multi-functional, piezoceramic-based material can also be used for reinforced concrete buildings for structural health monitoring. According to Song et al., as well as Saafi and Romine the disclosed system can monitor internal stresses, cracks and other physical forces in the structure during the life span [44]-[47]. It also has the ability of providing early indication of the health of the structure before a failure can occur.

G. Adhesives

An interesting application area of NT in construction industry is the adhesives, which have revolutionized from the past to the current. Although many of the formerly used adhesives contained environmentally harmful substances, such as formaldehyde, NT offers many opportunities for environmentally conscious ones [45].

Much of the inspiration for nano-enhanced adhesives comes from nature. Adopting principles and mechanisms of nature is referred to as biomimicry. Examples of biomimicry can be found in the water-repellent properties of nanocoatings, which take their lessons from the hydrophobic lotus leaf, and in a new generation of nano-adhesives now under investigation, which are based on the remarkable feet of the gecko that enable it to climb walls and even ceilings (Fig. 10). The gecko's toe is soft and smooth, and not sticky. If a gecko toe is pressed onto a hard surface it does not stick. The toe only adheres when the microfibers (setae) are engaged, by dragging or sliding the toe parallel to the surface. If toes were sticky like tape, it would be difficult for a gecko to walk or run, as it

would be too hard to pull its feet up. Today there are many groups working on gecko-inspired adhesive materials for a sustainable construction industry [46].

V. CHALLENGES IN THE ADOPTION OF NANOTECHNOLOGY

In the last decade, NT products and applications showed significant environmental benefits including energy savings and reduced reliance on non-renewable resources, as well as reduced waste, toxicity and carbon emissions. The benefits of NT for a sustainable construction industry will accrue first from coatings and insulating materials available today, followed by advances in solar technology, lighting, air and water purification, and structural materials and fire protection, as well.

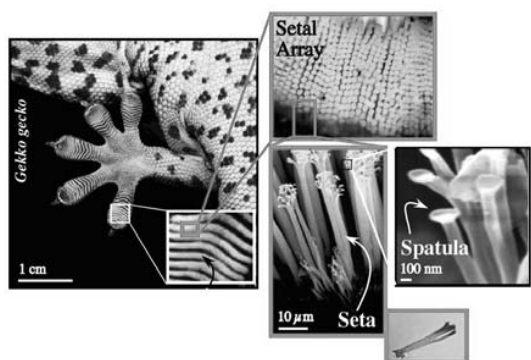


Fig. 10 The gecko toe and the setae, which are adhesive [46]

Increasing demand for more sustainable buildings necessarily require the integration of new and environmentally conscious technologies and materials. As with most developing technologies, NT has many challenges and limitations during adoption due to cost of production, as well as accurately defined environmental and health impacts. The application of NT to a market as broad as the construction industry poses many challenges for manufacturer, professionals and government agencies. According to G. Elvin the primary obstacles that limit the adoption of NT in the industry are; (i) high cost of nanomaterials and nanoproducts; (ii) the resistance of construction industry to innovations; and (iii) public rejection of this technology due to the potential health impacts [23].

The rapid adoption of NT into the construction industry is being slowed down by the mismatch between the short-term financial benefits and the high cost of nanoproducts relative to conventional building materials. Although most of short-term on developing the production techniques, very small quantities of nanomaterials can be produced relative to the quantities of conventional building materials, due to the inefficient fabrication infrastructure. In addition, although NT based construction products provide many advantages to the design and construction of buildings, the production of these products require a lot of energy. In this context, it creates an environmental challenge to the construction industry. Sustainability and environmental issues caused by growing

economic development has gained worldwide attention. Since the construction industry is heavily involved in the economic development and consumes great amount of resources and energy, its impact on environment is significant. Therefore, it is necessary and urgent to regulate the construction and its related performance to sustainability. More research and practice efforts are needed to save energy, reduce resource consumption, and avoid impacts on the built and natural environment.

VI. ISSUES RELATED WITH THE HEALTH OF HUMANS AND ENVIRONMENT

Although the integration of NT with the construction industry is very recent, it has already raised issues related with its potential impacts on human health and environment. As the production and use of nanomaterials increase, the possibility of their release also increases, thus raising up the potential adverse impacts.

Manufactured nanomaterials enter the environment during the production, transportation, use and disposal [47]. Exposure to nanomaterials and nanoparticles during these processes is the primary reason for the increase in adverse impacts on human health. Impact of nanomaterials during manufacturing and use may occur through three mechanisms: Inhalation, dermal contact and ingestion. Nanomaterials embedded in construction materials or used in other applications and products can cause cellular toxicity via multiple groups (Fig. 11). The important mechanisms of cytotoxic nanomaterials include disruption of cell wall integrity (e.g. single-walled nanotubes), nucleic acid damage (e.g. multiple-walled nanotubes), generation of reactive oxygen species that exert oxidative stress (e.g. TiO_2), release of toxic heavy metals or other components, and direct oxidation upon contact with cell constituents. Grassian et al. [48] studied the effects related to the inhalation of TiO_2 particles with a primary particle size between 2 and 5 nm, reporting lung inflammation. Ultra-fine SiO_2 nanoparticles also have been reported as human carcinogens [49]. Hallock et al. [50] recommend that the use of nanoparticles should be made with the same care already used in institutions for materials of unknown toxicity, i.e., by using air extraction devices to prevent inhalation and gloves to prevent dermal contact. Singh et al. [51] mentioned the possibility of DNA damage resulting in later cancer development. Other authors [52] believe that the nanotoxicity risk depends on the nanoparticles types, sizes, characteristics and concentration volume. Bystrzejewska-Piotrowska et al. [53] have recently carried out an extended literature review on this subject. These authors mentioned that Environment Protection Agency has considered that CNTs are a new form of carbon that must be treated under the toxic products Act. They also mentioned that nanoparticles may be responsible for a new kind of problem, the appearance of nanowastes. They suggest that products containing nanoparticles should be labeled in order to facilitate future separation and recycling procedures.

Currently, due to the lack of case studies, information on dominant exposure routes, potential exposure levels and/or

material toxicity is not adequate. Research is continuing to understand how these unique modes of biological interaction may lead to specific health effects.

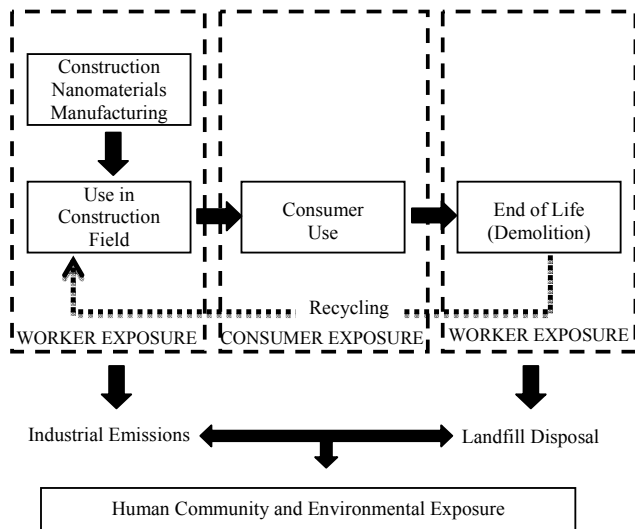


Fig. 11 Possible exposure routes during the lifecycle of construction materials; manufactured nanomaterials enter the environment during manufacturing, transporting, using in the field or by consumers, disposing, and also in the recycling process as well. Exposure to nanomaterials and nanoparticles during any of these processes is the primary reason for the increase in adverse impacts on human health [49]

VII. CONCLUSION

Nanotechnology is a rapidly expanding and innovating area of research, where novel properties of materials manufactures on the nanoscale can be utilized for the benefit of construction industry. The contribution of this technology to the construction industry has the potential to improve the environmental quality of buildings, change the service life and life-cycle costs, as well. The use of this technology should be considered not only for enhancing properties of traditional materials, but also for monitoring health and safety of structures, and for the context of energy consumption, as well. Although the cost of many nanotechnology materials is relatively high, it is expected to decrease over time.

The most problematic issue in the application of nanotechnology materials is that the various effects of these materials on the environment and human health are not clearly defined yet. Typical potential problems of nano scale materials include leaching of materials into the water resources, and seas, as well, release of nanoparticles into the air generating dust and exposure to harmful materials during construction, maintenance and use. Various investigations focus on uncertainty regarding the potential effects of nanomaterials and nanoparticles that significantly have different characteristic from the traditional construction materials. For a sustainable environment, all the materials used in the buildings must be compatible with the environment and human health in order not to conflict with the concept and task of

sustainability.

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