Architectural Engineering Technology

Leone, J Architec Eng Technol 2012, 1:1
http://dx.doi.org/10.4172/2168-9717.1000102

Review Article

Open Access

Nanotechnology for Architecture. Innovation and Eco-Efficiency of Nanostructured Cement-Based Materials

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Abstract

The paper explores the recent innovations in architecture materials developed through nanotechnology, based on the design of material properties in order to obtain specific performances. In particular, nanostructured cementitious materials, represent an interesting application of nanotechnology in the construction industry, considering the significant performance advantages compared to conventional products and the potential in reduction of resources and energy consumption throughout the life cycle connected to their use. To understand the relevance of these innovations, an approach aimed at identifying the possible impact on design and construction is required, considering the benefits achievable through a conscious use of nanotechnology, without neglecting the scientific issues still open and risk factors for humans and environment related to their uncontrolled use. The specific focus on the characteristics and potential applications of nanostructured cement-based materials is intended to reaffirm the need to develop an adequate level of knowledge internal to architectural disciplines on nanotechnology-related innovations, starting from the prominent role that cement and concrete plays in the construction industry.

Keywords: Nanotechnology; Architecture; Nanostructured materials; Cement; Concrete; Eco-efficiency

Introduction

Nanotechnology represents one of the fastest growing industrial sectors in recent years worldwide. The construction industry begins to look with increasing attention to nanotech innovations, identified as an important resource to give a new impulse to market growth. Nanotechnology applied to building materials represents an example of how innovation increasingly combines dematerialization, eco-efficiency and knowledge-based approach to develop new classes of products – often substitute of conventional technologies – with the aim of opening new market sectors based on the paradigm of the green high-tech[1].

Recent innovations in construction materials driven by nanotechnologies application are based on the design of material properties in order to obtain the required performances, developing sophisticated transformation processes that allow to realize custom-fit products for specific architectural applications.

The development of "designable" materials and components marked the evolution of architectural languages, evolving from a "muscular" exhibition of technology (typical of the "high-tech" architecture of the past decades) to a widespread microinnovation not always visible to the naked eye. Since the beginning of the twenty-first century, this perspective has changed mainly due to the "change of scale" of possible modifications, which have passed from micro to nano scale, moving further the boundary of possible transformation and exponentially expanding both the potential and the risks associated with the use of increasingly advanced and smart materials capable of expressing both high and customizable performance, reliability and durability, minimal environmental impacts, but also unknown effects.

Even though advanced materials – and, among these, those developed through the application of nanotechnology and biotechnology – are capable of offering effective responses to economic and environmental issues in the industrial sector, only in recent years the architectural have disciplines begun to acquire the technical knowledge needed to use them and to wonder about the implications in the design process. Nanostructured cementitious materials represent an interesting development of nanotechnologies in construction sector, showing a higher level of performances and a lower consumption of both material and energy resources if compared to the traditional cement-based products. Starting from the comprehension of chemical and physical phenomena occurring at the nanoscale, which are responsible of the final performances of cementitious materials, it is possible to optimize properties such as mechanical strength, durability and resistance to aggressive environments. In other cases, the integration of nanomaterials in the cement mix can lead to nanocomposites with novel properties, such as self-cleaning, self-monitoring or anti-pollution.

Nanotechnology and Architecture

The origin of nanotechnology

Over 50 years have passed since the Nobel Prize physicist Richard P. Feynman, with the lecture at the California Institute of Technology entitled "There's plenty of room at the bottom" [1] has opened the way for innovations related to nanotechnology, prefiguring the possibilities associated with the transformation of matter at the molecular level. Studies conducted by Feynman and his intuitions have laid the basis for a radical transformation of techno-scientific horizon, starting from the possibility of miniaturization of computers to which much of technological innovations produced in the last fifty years is owed.

Despite the "intellectual authorship" of Feynman, the term "nanotechnology" was coined in 1974 by Norio Taniguchi of Tokyo Science University, which defines it as a process of reorganization of matter atom-by-atom or molecule-by-molecule [2]. After twelve years, in 1986, the potential of this new concept of science and technology was

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Received December 08, 2011; **Accepted** May 24, 2012; **Published** May 28, 2012

Citation: Leone MF (2012) Nanotechnology for Architecture. Innovation and Eco-Efficiency of Nanostructured Cement-Based Materials. J Architec Eng Technol 1:101. doi:10.4172/2168-9717.1000102

better clarified through the work of Kim Eric Drexler entitled "Engines of creation: the coming era of nanotechnology" [3], which prefigures many of the goals achieved afterwards in science and production sectors. Drexler defines nanotechnology as the thorough, inexpensive control of the structure of matter based on molecule-by-molecule control of products and by-products; the products and processes of molecular manufacturing, including molecular machinery [4][2] .

Since then, nanotechnologies emerged in many industrial sectors, introducing products with new features and benefits, also modifying the way of conceiving the relationship between the matter and its possible transformations.

The study of chemical and physical phenomena at the nanoscale and the application of nanotechnology in the production processes of various materials have produced significant innovations in almost all sectors. The widespread opinion is that the impact of these technologies will have effects comparable to the diffusion of antibiotics and plastics, involving large market sectors, including construction [5]. Through the use of nanotechnology it is possible to develop new materials that can respond to specific functions, creating products and systems with unique properties arising from the particular molecular structure or implementing quality and performances of existing products. The "appearance" of nanotechnology in sectors such as electronics, biomedical and diagnostics is strongly related to the need for an increasing miniaturization of components to improve product performance, ensuring high reliability and control ability.

The most delayed research sector is probably the study of possible risk factors related to nanotechnology, since the effects of nanoparticles on humans and environment are still largely unknown to researchers themselves, and only in recent years several countries (including the European Union) have introduced monitoring and protection policies [6]. Such uncertainty is even more surprising if we consider that the main "promises" of nanotechnology are specifically related to the reduction of the environmental impact of production processes.

Nanostructured materials and nanocomposites in construction

Innovations related to nanomaterials – i.e. materials with at least one dimension below 100 nm such as nanotubes, nanowires, nanoparticles, etc. – are by far the leading sector of nanotechnology research, even if it is misleading to identify nanotechnology applied to materials with the use of nanomaterials embedded in conventional materials. These are in fact commonly known as nanocomposites, representing only a part of the broader category of nanostructured materials that are characterized by a controlled molecular structure, even when the production process does not require the use of nanomaterials.

In the case of many building materials, both those cement-based and certain types of polymers or composite materials, the observation of the physical-chemical properties at the nanoscale allows to test the properties with such a degree of precision that is possible to "correct" and optimize the characteristics of material's nanostructures depending on the final performance expected, even without the addition of nanomaterials. In high performance concrete, for example, the modification of the mix-design (depending on the type and size of the aggregates, the type of additives and the water/cement ratio) can increase of mechanical strength and durability.

It is then possible to outline two main categories of nanostructured materials, mainly distinguished by the fact of being or not added with nanomaterials.

A "nanostructured material" can be defined as a traditional material – such as steel, cement, glass or polymers – admixed in mass or surface with nanomaterials (nanocomposite) or modified in its chemical and physical structure through observation, testing and characterization of the properties at the nanoscale (nanoengineering). In both cases the original characteristics of the materials are modified and improved in order to obtain specific performances, usually not comparable to those shown by the original materials.

Nanotech products

The construction sector was among the first, since the early 90s, to be identified as a promising application area for nanotechnology. To date, however, the innovations have not yet produced the expected results and it is a sector still in a generally embryonic stage [7-10].

The stated objectives of the subjects engaged in research on nanomaterials and nanosystems mainly concern a shift from a materials development based on resources exploitation to one based on knowledge, able to transform the construction sector into an area with a high technological potential, focused on innovation, competitiveness, environmental protection and social security [11]. This is linked to some key issues, such as a more rational use of raw materials, the cost reduction in product life cycle, the production of new materials with high performance levels, the improvement of product efficiency and durability.

This framework returns a scenario in the short and medium term (5-15 years), in which the increased familiarity with new products and systems based on nanotechnology – as well as a check of their reliability through the development of pilot projects – will expand applications in architecture. At present, the most promising applications concern nanostructured coatings – such as paint and surface treatments – anti-stain and anti-pollution, resistant to abrasion and aggressive agents, photoreactive, insulating, transparent and anti-UV. Significant advancements include the ability to structure at the nanoscale level conventional materials – especially steel, ceramics, concrete and composite materials – both through the addition of nanomaterials in production phase, both through nanoengineering, in order to minimize the imperfections of the finished product.

Nanotechnology allows achieving, for example, concrete with characteristics similar to steel for what concerns relationship between weight and carrying capacity, ceramic materials of greater strength and toughness, metals with greater hardness, high yield resistance and special electrical properties. In the field of polymers greater mechanical strength, improved resistance to heat and chemicals, electrical conductivity, resistance to weathering and aging can be achieved.

With the diffusion of these innovations a material will no longer be uniquely associated with some restricted functions, but there will rather be different ways to achieve the needed performances, depending on the material chosen by the designer. Nanotechnology also allows synthesizing new classes of materials with completely new properties, such as transparent ceramics or insulating materials, invisible insulating coatings, as well as a new generation of smart materials with special properties of interface with the external environment and self-regulation.

The control of the nanostructures in different building materials and the possibility of exploiting the special properties of nanomaterials, make potentially feasible a high variety of products with different functions: structure, envelope, coating, equipment and sensors.

The main innovative feature is the possibility to vary the performance of products and systems in an extremely versatile way. The proliferation of "nano-modified" products is linked in part to the easiness, once placed on the market a "nanotech product", to expand its range by adding and combining specific performance.

Research and innovation in the construction industry

In Europe, research and investment on nanotechnology are set to grow significantly in coming years. An indicator of this trend is, for example, the relevance of the topic within the VII Framework Programme, which identifies the area of "Nanosciences, Nanotechnologies, Materials and new Production Technologies" among the priority areas for economic and industrial development, considering the materials with novel properties the key to the future competitiveness of European industry and the basis for technical progress[3] .

In the construction sector, the current phase is characterized by a rapidly expanding market of nanotechnology applied to materials, products and systems. Despite the demand in this sector is so far rather limited (in the United States in 2006 amounted to only 20 million dollars), a strong growth is envisaged, thus leading to a widening of the market, approximately equal to 100 million dollars in 2015 and about 1.75 billion in 2025 [12-14].

The focus of the construction industry on nanotechnology is strongly oriented by the market logic, that require a new segmentation and concentration of resources on sectors characterised by high growth, in order to attract demand and gain positions of strength, using therefore a kind of "nanotech branding". For these subjects, the main entry barriers are the need to acquire tools and knowledge to develop new processing technologies and new products.

In recent years the more general development of knowledge-based technologies has significantly changed the characteristics of the construction market. The possibility of obtaining multifunctional or, on the contrary, highly specialized materials, allow to multiply the possibilities of innovation declining embedded performance depending on the product and the specific application, according to a tailor-made and custom-fit logic [15].

The optimal strategy requires major manufacturers to enter the market with products based on a few key-performances and to expand the supply in relation to technology developments and market responses. Covered by the patent related to the "nano-innovation", the corporations can structure a network of business partners with a twofold objective: to expand their market and their visibility and to receive useful feedback that can contribute to the evolution of originating products.

Small and medium-sized enterprises get immediate benefits from such a partnership model: they can expand the product range based on innovative and competitive technologies and at the same time – thanks to the technical and scientific support of the main manufacturers in the transfer of know-how – they can develop by themselves incremental innovations on existing products, launch new products or activate new business functions, from R&D to external consultancy.

The environmental and social impacts of nanotechnology

A key factor to consider in relation to the increasing transfer of nanotechnology in the construction industry is the need to control environmental and social impacts. In industry sectors such as aerospace production levels stood on a modest scale and the careful control of all stages, from production to assembly, is an essential condition for the testing of new technologies. The fear is that in the construction sector – with very high production levels and in which below the main producers the proper employ of products and systems is based on the competence of the contractors – the risks related to the diffusion of nanotechnology can be amplified. The answer to these problems lies in the ability of the main producers to ensure and certify the efficiency and environmental performance of processes and products, and to offer a constant interface with designers and companies in order to reduce the conditions of technical risk during the life-cycle.

Due to the increasing evidence of these issues a specific discipline has been developed, the green nanotechnology, with the goal of producing nanomaterials and nanostructured products that minimize the possible risks to the environment or human health, offering at the same innovative solutions to the growing environmental challenges [16-18]. Promoters of green nanotechnology intend to apply the principles of sustainable chemistry[4] and engineering, in order to develop industrial processes that employ non-toxic substances, implemented at low temperature and with small amounts of primary energy, exploiting renewable resources, integrating a life cycle thinking logic to new products design and manufacturing. This different approach has led to some important results, especially in relation to the energy efficiency of manufacturing processes of nanomaterials, defining an LCA approach (Life Cycle Assessment) applicable to them[5].

The actual knowledge of the environmental impacts is an essential resource for the application of nanostructured materials in the construction industry – considering the current demand for increasingly efficient and "clean" technologies – and is part of a wider issue related to the assessment of technological options in relation to the life-cycle impact of construction products. In the construction industry, facing the risk of a "new asbestos" [19,20], a significant step forward may be the classification and standardization of processes and products related to nanomaterials [21,22], in order to gather measurable and comparable data through which orient choices related to their employment, promoting environmental certification and labelling systems.

At present – among the great confidence expressed by researchers and government agencies and the warnings coming from associations and scientific community – yet do not exist appropriate systems of regulation and control, also because a full awareness of the categories of products and processes to be tested is still missing [23].

Nanotechnology and architecture

The growing attention in relation to the potential of nanotechnology in architecture is derived from multiple factors that affect both functional and aesthetic aspects of buildings, also involving wider issues related to the possible contribution to the eco-efficiency of industrial processes and products. The potential associated with a complete transformation of the construction logics of the technical elements and the resulting architecture outcomes, including morphology aspects, is now emerging [24]. The possibilities linked with the development of industrial products based on nanotechnology begin to stimulate design researches aimed at exploiting the unique properties of new materials, which allow-for example – the creation of extremely thin, ultra-insulating and self-regulating transparent shells, thin and light structures with a resistance up to a hundred times greater than steel, buildings able to self-repair technical elements or to send "reports" on the functioning of various parts and components [25,26].

Nanotech innovations currently available seem therefore not only able to have a significant impact on the characteristics and performance of building components, but also, in perspective, to bring changes in the relationship between the designer and the conventional "palette" of materials used in architectural design.

At present, the diffusion of new building materials developed through nanotechnology is mostly due to the efforts made by industries and companies that transformed into products the scientific advances of recent years. However, these are usually products intended to replace conventional technologies that do not cause significant changes in the design and manufacturing approach (e.g., special glass and insulation materials, protective and functionalized coatings, etc.). The "first generation" of nanostructured materials, while introducing additional performance to components and systems in which they are applied, does not seem to have tangible impacts on the possible evolution of the architectural language, which is widely considered the main aspect of the "nano-architecture" of the future [27].

According to the architects and designers "pioneers" of nanotech architecture[6], new materials will allow the realisation of buildings able to create a dynamic relationship with environmental factors and with electrical and electronic impulses activated by man, modifying their performance, their appearance and even their shape in relation to external stimuli, in order to ensure comfort and energy savings, but also to use the architecture itself as a communication "interface", enhancing the possibilities of information exchange and mutual interaction. One of the main aspects concerning the contribution of nanotechnology to the architectural design is in fact linked to the possibility of creating a new generation of green buildings characterized by the use of innovative materials able to connect the needs of low environmental impact together with aesthetic and communicative aspects of architecture [28], as in the Marwan Al-Sayed project for the new World Trade Center in New York, characterized by a nanostructured high-energy performance shell, with photo and thermo-chromic properties that allow to modify the colour, level of transparency and of heat transmission.

The relevance of such changes, already prefigured in some recent pilot projects, is such that some authors claim that in the future «the distinctions between living and inanimate matter are no longer certain; we can no longer distinguish between what is natural and what is artificial and we will do what we want, by assembling the reality a molecule at a time[7].

Nanotech Cement

Nanotechnology for cement-based materials

The specific focus on the characteristics and potential applications of nanostructured cement-based materials is intended to reaffirm the need to develop an adequate level of knowledge internal to architectural disciplines on nanotechnology-related innovations – even considering the essentially interdisciplinary nature of the study on nanostructured materials and the necessary interactions with the fields of engineering, chemistry and materials technology – starting from the prominent role that cement and concrete plays in the construction industry.

The performances expressed by nanostructured cementitious materials – a wide category that includes products for structural or finishing applications, components for building envelope or horizontal surfaces – determine a value added both in terms of eco-efficiency of products and processes, and in terms of aesthetics.

Many of the innovations related to nanotech cement and concrete are in fact related to the optimization of physical-mechanical properties and to the introduction of additional performances that allow considerable material and energy resources savings in each stage of the product life cycle, combined to the possibility of achieving original design applications and experimenting new architectural languages.

These issues are particularly relevant and up-to-date, considering on one hand the enormous levels of production and pollution related to the cement industry that limit the application of cementitious materials in a sustainable perspective, and on the other the conventional "engineering" design approach, that often reduce the expressive potential of cement and concrete, once heritage of the great masters of modern architecture, from Gaudi, Mendelsohn, Saarinen and Wright, to Nervi, Morandi, Musmeci and Candela.

Nanotechnology allows for instance to analyze, modify and control the hydration of cement in mortar and concrete, improving overall performance in relation to the mass, thus allowing to obtain excellent mechanical, chemical and physical properties with less material. Moreover, the calcium-silicate-hydrate (CSH) structure generated by the reaction between the different chemical components in the cement hydration process – responsible of the physical and mechanical properties including shrinkage, creep, porosity, permeability and elasticity – can be modified to achieve a higher durability or to realise mixtures characterized by an improved workability over time. The study of the behaviour of the particles that constitute the CSH gel, about 2 nm in size, represents a major area of nanotechnology research related to cementitious materials [29,30], identifying in these nanostructures a kind of "genetic code" of concrete and the imprint of the nanomechanical properties responsible of the final properties of the material[8].

In other cases, in order to enhance the final performance, nanoparticles or nanofillers are added to the cement mixture. The addition of various types of nanomaterials to create cement-based nanocomposites also allows introducing novel properties, such as the ability to absorb air pollutants or self-monitor the material behaviour over time. Compared with conventional additives, the addition of small amounts of nanoparticles can change the rheological behaviour of cement and enhance specific properties.

Unlike other types of materials, where the contribution of nanotechnology is closely connected to the use of functionalized nanoparticles to improve certain characteristics (with still uncertain results about the levels of eco-efficiency expressed), in the case of cementitious materials the most promising innovations concern the nanoengineering of the material aimed at the reduction of material and energy consumption especially in the production phase (by far the most impactful in the life cycle of cementitious materials). This objective is reached through a design approach to the material that follows two different paths. On one hand it is possible to substitute the raw materials[9] used in order to lower the level of energy required during the clinker burning process, on the other it is possible to design cements and concretes with improved mechanical properties, thus reducing the amount of material used (e.g. structures with thinner sections and equal carrying capacity) and consequently the energy consumption and pollutant emissions.

The use of ultra-fine aggregates (in some cases even nano-sized) or nanostructured admixtures allows to combine improved mechanical performance, rheological properties and workability (and therefore a greater efficiency, in terms of environmental impacts, of the construction phases), with an increase of the durability due to a more compact structure that prevents the attack of chemical and atmospheric agents.

The ability to realise tailor-made products – where the final

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performance requested become the input for the design of the material – or multifunctional products – suitable for different applications (this is the case, for example, some mortars used for both structural restoration and finishing application) – results in the possibility of optimizing the material according to the needs of project and site, reducing time and costs of construction [31].

Nanostructured cementitious materials seem therefore to ensure an effective response in relation to some parameters that characterize eco-efficient products, such as material and energy resources saving throughout the life cycle, a more rational use of raw materials [32,33], higher and more reliable performance in use compared to conventional products, a high durability that allows to reduce and simplify maintenance operations, as well as a peculiar response to environmental conditions (self-cleaning, self-monitoring, photocatalysis, etc.).

The comparison of the life cycle impacts between ultra-high-performance concrete (UHPC) and conventional reinforced concrete[10], for example, shows a significant reduction in the consumption of material (about 6 times lower) and energy resources (around 40%), as well as lower emissions of greenhouse gases (about 50%). The environmental impacts in production and processing phases are lower even if compared with steel structures (-40% in terms of embodied energy and greenhouse gas emissions). These characteristics have allowed the UHPC to obtain LEED certification (Leadership in Energy and Environmental Design) in United States and Canada.

The possibilities offered by the development of nanotechnologies bring to a new conception of cement-based materials, which can be designed "on demand", according to the final performance required for a given application (reinforced concrete, mortars, plasters, paints, etc.).

It is not always easy to identify whether in the production process of a given type of product there is a more or less consistent use of nanoparticles to reach the final properties. Most manufacturers specify if a nanotech-based product has no nanoparticles added, but their use is rarely declared because still there are no regulations that require such specifications.

Anyway, in most of the "nanotech" products the health and environmental issues related to the use of nanoparticles do not concern the finished product (when incorporated in the crystalline structure of the material), but mainly the production phases. Most of nanomaterials currently used in cement-based products are synthesized by bottom-up techniques (e.g., Sol-Gel). These materials are incorporated into colloidal suspensions or additives which are impossible to distinguish, to the naked eye, from traditional additives. In other cases, the nanofillers used in the laboratory to develop the products can be substituted by larger particles when passing the phase of industrial production, due to technical difficulties related to mass production aspects or to protect the brand of "sustainable product".

Nanotech cementitious materials in new construction and building retrofit

The optimization and customization of final performances given by the nanotech approach to the design of cementitious materials has opened the way to many innovative architectural applications, aimed at exploiting the potential of the different types of products currently available on the market.

Some of the first architectural applications of nanostructured cementitious materials concerned the use of photocatalytic concrete elements. Richard Meier's research for the white "concrete sails" of Dives in Misericordia church in Rome brought to the choice of exploiting the self-cleaning properties of titanium dioxide to preserve the aesthetic properties of the precast curved concrete panels. The same technology was later adopted for the Ara Pacis Museum, by using photocatalytic cement based paint.

In other cases, special concretes developed through nanostructured additives and instruments for the characterization of mix-design at the nanoscale allowed to significantly reduce construction time (curing times lowered from 28 days to 6-8 hours) or to realise high strength structural elements with a reduced use of passive reinforcement. In these cases the greater freedom in the structural design is translated into architectures characterised by slender structures, large spans and structural elements shaped in a plastic way, whose surfaces are free of imperfections, characterised by customizable textures and a high resistance to weathering and aging with no need for additional surface treatments. The improvement of physical and mechanical properties of cements and concretes allows reducing the load-bearing sections, with thicknesses nearer to steel structures rather than to conventional reinforced concrete structural elements. Innovative high-strength concretes (UHPC - Ultra High Performance Concrete, nanosilica concrete, etc.) are being used in architectures where the shape of the structural elements is optimized and designed to minimize the need for passive reinforcement, with a value-added due to nanotechnology innovation both in terms of performance and aesthetics: prefabricated elements that can withstand cantilevers up to 7 m almost without steel reinforcement (Rudy Ricciotti, Villa Navarra in Le Muy) and ultra thin pedestrian bridges (Rudy Ricciotti, Footbridge of Peace in Seoul, with a thickness of 30 mm; the "flying carpet" by T. Ungerer in Strasbourg, 25 mm).

Also in the field of building retrofit innovative technologies based on the use of nanostructured cementitious materials represent an area that is likely to have significant development. Cement-based nanostructured products – concretes, mortars and paints – can be used for façade restoration, for the structural reparation of degraded concrete elements. Structural rehabilitation through nanostructured mortars allow to significantly reduce construction time, waste production and water consumption. Other interventions regard restoration of plasters, paints and road surfaces through self-cleaning and anti-pollution photocatalytic coatings. In Bergamo the use of photocatalytic paving blocks for road resurfacing has been tested, resulting in a reduction of NO_x values, especially at head height, in the order of 40%[11]. Experimental application of photocatalytic paints on the internal vaults and horizontal surfaces of road galleries (e.g., Traforo del Tritone[12] in Rome, via Porpora tunnel[13] in Milan), have shown how the use of such technology avoids the blackening due to exhaust gases and reduce the concentration of pollutants from 30 to 40%. Since the photocatalytic action is activated by solar radiation, these projects provided the integration of a new lighting system with UV lamps and special self-cleaning glasses.

The benefit in terms of environmental impact is accompanied by an increase in costs which is relatively low, especially considering the reduced cost of maintenance operations along time due to the self-cleaning properties. For a five-storey façade, for example, the use of photocatalytic paints determine an extra cost of about 10-12%, while in the case of paving blocks the cost increase compared to a traditional asphalt is approximately of 15%.

Nanotech Products

Nanosilica cement

Silica (SiO_2) is a common component of conventional cement mix, but the use of nanosilica particles leads to a material's micro and nanostructure more dense and viscous, thus improving workability and mechanical properties (compressive strength from 3 to 6 times higher) as well as reducing carbonation process. Nanosilica particles react with the calcium hydroxide released during cement hydration, thus increasing the amount of binder in the cement matrix. The addition of nanosilica (about 1.5% of weight) is generally made through admixtures and begins to be used for the realization of high performance concretes or cement mortars with high mechanical strength, workability and durability. Recently the use of nanosilica (diameter 5-50 nm) has been tested[14] as a VMA (Viscosity Modifying Agent) in SCC (Self Compacting Concrete) treated with mineral additives (ground limestone, fly ash, etc.) [34].

Photocatalytic cement

Since the mid-'90s, the possibility of providing a contribution to air pollution reduction through the use of construction materials, such as glass and cement, containing photocatalysts has been explored. The addition of titanium dioxide nanoparticles makes the cementitious material hydrophilic and its surface self-cleaning. This particular feature also introduces antibacterial properties and the ability to degrade air pollutants must be added [35].

Under optimal level of lighting and photocatalyst's activity, it is estimated that 1000 m^2 of photocatalytic surface are able to clean an air volume of 200,000 m^3 per day (considering 10 hours of light per day). It is then possible to hypothesize that the treatment of about 15% of the external surfaces of buildings and roads would reduce significantly the level of pollution in urban environments. The indoor effectiveness of photocatalysis has been recently studied, demonstrating that also indirect sunlight entering the building is able to activate the process.

Waterproof concrete

The development of special nanostructured admixtures has made possible the improvement of water resistance in cement mixes, as well as the introduction of self-repair ability. These admixtures, water-based colloidal suspensions of inorganic agents, are characterised by a peculiar crystalline structure.

Once added at a rate of 2-3% of weight, without any special operating precautions, they are able to penetrate into the crystalline structure of the concrete and react in the early stages of hydration, filling with a large number of nanocrystals the capillary voids responsible for the material porosity and permeability to water. Once treated, the material also shows a significant resistance to aggressive agents and increased resistance to freeze-thaw cycles, preserving an adequate level of breathability. Thanks to the compactness of the micro and nanostructure of the material, the compressive strength can be increased up to 25%, while the reactivity of the admixture during the curing time allows the self-reparation of shrinkage cracks.

3SC concrete

3SC concrete[15] (Self-Compacting, Self-Curing, Self-Compressive) represents an evolution of the Self-Compacting Concrete (SCC). This innovative technology reduces the energy required for construction of reinforced concrete structures, as well as construction costs and time (50% and 80% respectively). The three typical properties of 3SC concrete are obtained through the integration of superplasticizers (admixtures based on polycarboxylate ethers), Viscosity Modifiyng Agents (VMA), Shrinkage Reducing Admixtures, (SRA, based on polyglycol ethers) and expansive agents (based on calcium oxide).

3SC concrete shows considerable benefits during the transportation to the construction site, since it is possible to delay the hydration process of fresh concrete for the first two hours, saving the workability also with critical conditions of temperature and humidity. In these cases, the use of nanostructured accelerating admixtures allows an adequate development of mechanical performance during the different stages of maturation. Once casted on site, 3SC concrete also allows to remove the formworks after only 6-8 hours (instead of the conventional 28 days).

UHPC (Ultra High Performance Concrete)

The UHPC (Ultra High Performance Concrete) is a "conventional" composite material, consisting of a cement matrix and short polymer or metal fiber reinforcement that determines the improvement of mechanical and durability properties. Generally there are no nanoparticles added in a typical UHPC mixture, and therefore it cannot be considered as a nanocomposite, but rather as a nano-engineered concrete obtained through the control of nanostructures responsible of the material's final properties [36-38]. The development of UHPC has been made possible by the observation at the nanoscale of the hydration process of cement, thus allowing to select a particular mix-design balancing the type and size of aggregates, water-cement ratio and admixtures to be used.

The experiments and tests carried out have laid the basis for the development of innovative technical and design solutions. In France, in particular, the first guidelines for the design with UHPC have been published in 2004 [39], representing a major step towards a greater knowledge and the standardization of the technology.

Nanostructured cement mortars

The nanostructured mortars were among the first cement-based products for building rehabilitation involving the application of nanotechnology. Their use for retrofit interventions involving surface repair and structural rehabilitation of concrete elements considerably reduces waste production and water consumption on the construction site. The nanostructured mortars are not generally admixed with nanoparticles. The final properties are obtained through the use of fine aggregates, the modification of the cement matrix nanostructure through specific fillers and the combination of different types of admixtures that can be "stressed" in different ways to obtain different characteristics (better adhesion properties, higher mechanical strength, etc.).

The "nano-modification" influences the main characteristics of the material introducing a high compactness of the crystalline structure and resistance to shrinkage cracks through the elimination of capillary voids (hence the possibility of obtaining both very little and large thicknesses with the same product, ranging from 3 mm to 7 cm), a better link with aggregates and wall surface due to the creation of strong links at the nanoscale (which determines resistance to carbonation and freeze-thaw cycles, as well as waterproofing properties).

Cement-based insulating materials

Hybrid organic-inorganic composites represent an important research area in the field of nanostructured cement-based materials. Within this family it is possible to identify both polymer-based nanocomposites, in which inorganic nanofillers (nanosilica, aluminium powder, etc.) can be dispersed to improve some specific properties of the polymer matrix, and other types of materials that do not employ nanoparticles, based on the combination of polymers and inorganic materials (especially glass and concrete). The products in this second category are generally characterised by peculiar properties deriving by the creation of stable links at the nanoscale, similar to polymer chains.

The Hypucem (Hybrid Polyurethane Cement), for example, is a rigid foam, fire and water resistant, that combines, within a single material, excellent thermal insulation properties (λ = 0.025-0.040 W/mK) and thermal mass (it can be manufactured with different densities: 200-400-750 kg/m^3). The material shows both the properties of an autoclaved aerated concrete (breathable, lightweight, with good compressive strength, fire resistance, good compatibility with mortars and plasters) and the properties of a polymer foam (thermal and acoustic insulation, ease of installation and processability).

Concrete with Carbon Nanotubes

Carbon nanotubes (CNTs) are among the most promising types of nanomaterials for their excellent electrical and mechanical properties and the many potential applications in the building sector. Several studies on concrete samples reinforced with carbon nanotubes (1% of the total weight) have been conducted, showing how the oxidation of water in the cement mixture and the reaction during the hydration process allows the creation a stable links with the cement matrix, leading to a significant increase in both compressive and flexural strength (respectively +25% and +8%). The use of a CNT reinforced concrete would allow to reduce the dimensions of structural sections, using an amount of material up to 10 times lower. The biggest obstacle, apart from the very high cost of the nanotubes, is the difficulty to obtain an homogeneous dispersion into the cement mix, since the CNTs tend to aggregate forming interconnected microstructures, while to exploit the mechanical properties it would be necessary to orient them exactly following the direction of the forces, contrasting the natural "random" aggregation mode of the material. This type of applications has not yet reached a significant level of maturity. In the best cases it has been demonstrated that it is possible to reduce shrinkage cracks through the use of nanotubes [40], while further studies are needed to identify the optimal mix-design and dispersion techniques.

Other research areas are geared towards the exploitation of the special electrical properties of carbon nanotubes in the cement matrix. These concrete-CNT nanocomposites would be able to interact with the external environment through electrical signals to monitor the internal stress states or to change their appearance through interaction with electro-chromic or electro-luminescent materials. In this case the orientation of the nanotubes is less affecting the final properties, since it is sufficient a uniform distribution within the matrix, avoiding localized densifications.

Applications of NEMS to r.c. Structures

The application of NEMS (Nano Electronical Mechanical Systems) in reinforced concrete structures is a particularly interesting innovation aimed at achieving a better understanding of the behaviour of concrete. NEMS devices integrate electrical and mechanical properties at the nanoscale and could allow measuring the basic characteristics of the material (density and viscosity, shrinkage, temperature, humidity, CO_2 concentration, pH) over time, as well as monitoring the stress states, the reinforcement corrosion or other structural damages. NEMS are currently tested as admixtures, but the goal is to apply them on existing structures through paints or sprays, also to get a better distribution on the surfaces to be monitored. In addition to the potential lowering of maintenance costs, the possibility of a continuous monitoring of concrete structures would result in a more comprehensive knowledge of internal forces distribution, thus optimizing structural shape and section, reducing the amounts of material used.

Conclusions: Nanotech Innovations and Sustainable Building

The contribution of nanotech innovations to the different types of construction materials and products represents an important resource to drive the choice of technology options and the buildings design in a eco-efficient perspective. It is already possible to identify in certain types of nanostructured materials a significant response to the need of reducing the environmental impacts of industrial processes in the construction field. Within a few years an increased ability in the control and manipulation of the nanoscale of the different types of materials – primarily resulting from a strengthening of the instruments through which investigate and understand the mechanisms that determine the chemical-physical characteristics and final properties – appears to be able to significantly modify the conventional construction rules as well as buildings performances and appearance.

Within the fundamental relationship between technology and design, nanotechnologies determines interactions between design and manufacturing process, with possible implications on common design practice, introducing not only new materials but also new architectural concepts[16] .

The more the ability to control matter at the molecular level will be increased, the more it will be potentially possible its design and its manipulation; but because of the complexity of the "molecular design", without an adequate support of knowledge it will be increasingly difficult for architects and designers to know the exact composition of materials used in buildings or the potential consequences in the various phases of the life cycle.

Considering the wide range of application fields, the risk factors associated with the use of nanotech-based products must be extremely clear, pushing for a regulation at the international level which, combined with a greater awareness of designers, will allow to orient the construction industry toward innovations based on increasingly safe and efficient nanotechnology applications.

The architectural disciplines must then be able to support and guide the innovations produced in the field of nanotechnology, understanding the complexity of these processes in order to provide a cultural and technical support that may lead to a gradual diffusion of nanotechnology in construction, minimizing the possible risk factors and maximizing the benefits achieved through their conscious application in the field of the materials and the design of the architecture.

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Foot note references

1. In recent years the green high-tech has become the main business philosophy in almost all industries, an one of the main topics of Shanghai Expo in 2010.

2. Molecular manufacturing is the ability to build devices, machines or entire products by controlling the position of each atom. These are some of the most promising types of applications, yet more risky since, especially when combined with biotechnology and genetic engineering could lead, according to some authors, to mechanisms of mass control and manipulation, without considering the possible military applications. [20]

3. FP7 provide fundings for 3.475 billion euros, nearly twice the share allocated in the previous FP6 (1.9 billion). It is expected that in 2015 the market for nanotechnology in various industry sectors will grow between around 600 and 3.000 billion dollars.

4. See, among others, European Technology Platform for Sustainable Chemistry, www.suschem.org.

5. At the same time an update of the LCA methodology is required, to be in line with the nanotechnology perspective and the many economic, environmental, social and health issues related. Matthew JE, Julie BZ, Paul TA (2008) Toward Green Nano. E-factor analysis of several nanomaterial syntheses. Journal of Industrial Ecology 12: 316-328.Thomas PS, Igor L (2008) Coupling Multicriteria Decision Analysis and Life Cycle Assessment for Nanomaterials. Journal of Industrial Ecology 12: 282-285.

6. See, among others, Nanocity, http://www.nanocity.com, and Peter Yeadon, Year 2050: Cities in the Age of Nanotechnology.http://www.yeadon.net/yeadon/support/projects/0511/Year2050.pdf

7. Peter Yeadon, Future Studio, Lecture at Rhode Island School of Design (RISD), spring 2005.

8. One of the most important discoveries for the development of nanostructured cementitious materials concerns the understanding of different types of CSH formed during the hydration process, with low or high density. It was shown that approaching the nanometer size of particles constituting the CSH, it is possible to reach the highest density mathematically obtainable through the aggregation of spherical objects, equal to 74%, against 64% of the not-nanostructured CSH. The difference in density results in greater homogeneity of the mix and then in the optimization of the mechanical, rheological and durability properties.

9. MIT researchers, Franz Josef Ulm and Georgios Constantinides, starting from the study of the formation of nanoscale CSH layers, the elementary “building blocks” of concrete, investigated the possibility of substituting calcium with different types of minerals that react at lower temperatures but are able to create nanostructures similar to the CSH in density and chemical behavior.

Citation: Leone MF (2011) Nanotechnology for Architecture. Innovation and Eco-Efficiency of Nanostructured Cement-Based Materials. J Architec Eng Technol 1:101. doi:10.4172/2168-9717.1000102

Magnesium, in addition to these features, it is also a material readily available through industry recycling processes, which also helps to reduce the impact during extraction of raw materials. Currently the goal is to achieve, through these processes, a reduction of CO2 emissions in the production phase up to 50%.

10. The study has been carried out within the PhD research in Technology of Architecture at University of Napoli Federico II entitled “Innovazione tecnologica e materiali avanzati. Alte prestazioni ed eco-efficienza: nanotecnologie per l’evoluzione dei materiali cementizi”, (Mattia Federico Leone, 2009).
11. Data have been collected and monitored from 2006 to 2007 by Italcementi and ARPA Lombardia.
12. The Traforo del Tritone in Rome has been opened after a month of works in September 2007. The project has been sponsored and developed thanks to an agreement between Municipality of Rome, Italcementi and CIM (Calci Idrate Marcellina), with an overall cost of 500.000 €.
13. Studies carried out by ARPA Lombardia (Regional Environmental Protection Agency) after the retrofit of via Porpora Tunnel in Milan showed a reduction of NO of about 23%.
14. Cf. Mario Collepardi et al., “Influence of amorphous colloidal silica on the properties of Self Compacting Concretes”, in Proceedings of the international conference: Challenges in Concrete Construction – Innovation and Developments in Concrete Materials and Construction, Dundee, 2002, pp. 473-483.
15. Cf. Mario Collepardi et al., “3-Self-Concrete (3SC): la prossima sfida”, in Enco Journal, n. 24, 2003.
16. According to some authors, the extent of “nanotechnology revolution” in architecture seems to be even greater than other sectors, in terms of risks and opportuinities, considering the complexity and multiplicity of purposes, such as to «trascend traditional boundaries between living and non-living systems». George Elvin “NanoBioBuilding: nanotechnology, biotechnology, and the future of building”, in Proceedings of 2nd International Symposium on Nanotechnology in Construction, Bilbao, November 13-16, 2006.