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Nanoforum Report:

Nanotechnology and Construction

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Nanotechnology and Construction

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About Nanoforum

This European Union sponsored (FP5) Thematic Network provides a comprehensive source of information on all areas of nanotechnology to the business, scientific and social communities. The main vehicle for the thematic network is the dedicated website www.nanoforum.org. Nanoforum encompasses partners from different disciplines, brings together existing national and regional networks, shares best practice on dissemination of national, EU-wide and Venture Capital funding to boost SME creation, provides a means for the EU to interface with networks, stimulates nanotechnology in underdeveloped countries, stimulates young scientists, publicises good research and forms a network of knowledge and expertise.

Nanoforum aims to provide a linking framework for all nanotechnology activity within the European Community. It serves as a central location, from which to gain access to and information about research programmes, technological developments, funding opportunities and future activities in nanotechnology within the community.

The Nanoforum consortium consists of:

The Institute of Nanotechnology (UK)	www.nano.org.uk
VDI Technologiezentrum (Germany)	www.vditz.de/
CEA-Leti (France)	www-leti.cea.fr/uk/index-uk.htm
Malsch TechnoValuation (Netherlands)	www.malsch.demon.nl/
METU (Turkey)	www.physics.metu.edu.tr/
Monte Carlo Group (Bulgaria)	http://cluster.phys.uni-sofia.bg:8080/
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Executive Summary

Nanotechnology is the use of very small particles of material either by themselves or by their manipulation to create new large scale materials. The size of the particles, though, is very important because at the length scale of the nanometre, 10^{-9}m, the properties of the material actually become affected. The precise size at which these changes are manifested varies between materials, but is usually in the order of 100 nm or less.

Nanotechnology is not a new science and it is not a new technology. It is rather an extension of the sciences and technologies that have already been in development for many years and it is the logical progression of the work that has been done to examine the nature of our world at an ever smaller scale.

A nanometre is a billionth of a metre and at that size the classical mechanics of the everyday cross over into the quantum mechanics of the nano-world. The two are, of course, linked and recent developments in the study and manipulation of materials and processes at the nanoscale offer the tantalizing prospect of producing new macro materials, properties and products. The construction business will inevitably be a beneficiary of this nanotechnology; in fact it already is in the fields of concrete, steel and glass. Concrete is stronger, more durable and more easily placed, steel tougher and glass self-cleaning. Increased strength and durability are also a part of the drive to reduce the environmental footprint of the built environment by the efficient use of resources. This is achieved both prior to the construction process by a reduction in pollution during the production of materials (e.g. cement) and also in service, through efficient use of energy due to advancements in insulation. These and many other effects of nanotechnology on the industry are discussed in the report together with comments from researchers and industry professionals.

Two nano-sized particles that stand out in their application to construction materials are titanium dioxide (TiO_2) and carbon nanotubes (CNT's). The former is being used for its ability to break down dirt or pollution and then allow it to be washed off by rain water on everything from concrete to glass and the latter is being used to strengthen and monitor concrete. CNT's though, have many more properties, apart from exceptional strength, that are being researched in computing, aerospace and other areas and the construction industry will benefit directly or indirectly from those advancements as well.

Cost and the relatively small number of practical applications, for now, hold back much of the prospects for nanotechnology. However, construction also tends to be a fragmented, low research oriented and conservative endeavour and this plays against its adoption of new technologies, especially ones that appear so far removed from its core business. Materials though, as mentioned above, *are* construction's core business and the prospects for more changes are significant in the not too distant future, in fact, the researchers surveyed predicted that many advances would arrive within five years. The sheer size and scope of the construction industry means that the accompanying economic impact will be huge.

In order to capitalize on the effects of nanotechnology on the business, however, much more funding for construction related research, increased interdisciplinary working between researchers and communication between those researchers and industry is needed. If nothing else, changes outside the immediate scope of construction (e.g. demographic or environmental) will drive the need for innovation in the industry and if construction continues to ignore nanotechnology *it* will be the one left paying a fortune for a last minute ticket it could have had for a song if it had acted earlier.

Introduction

As people involved in construction, we are very familiar with the concept of getting raw materials, bringing them together in an organized way and then putting them together into a recognizable form. The finished product is a passive machine that does not change or adapt to the surroundings or environment. It works and slowly decays as it is used and abused by the environment and the owners of the project. It gets periodic maintenance but its main goal is to survive the demands made of it until it becomes obsolete and then it is dismantled and discarded to make way for something new. This is our role in society and we have performed it well for hundreds or thousands of years. Construction then is definitely not a new science or technology and yet it has undergone great changes over its history. The industry we see today is the result of a progression in science, technology, process and business.

In the same vein, nanotechnology is not a new science and it is not a new technology either. It is rather an extension of the sciences and technologies that have already been in development for many years and it is the logical progression of the work that has been done to examine the nature of our world at ever smaller and smaller scale.

So what is nanotechnology?

Nanotechnology is the use of very small pieces of material by themselves or their manipulation to create new large scale materials.

The size of the particles is the critical factor. At the nanoscale (anything from one hundred or more down to a few nanometres, or 10^{-9}m) material properties are altered from that of larger scales (the exact point at which this occurs depends on the material). The size boundary is kind of like the difference between standing on the edge of the Grand Canyon and taking a further step. There is a dramatic change in situation and this is what happens at the scale of nanotechnology. On one side, above the boundary, the world is pretty much as we experience it everyday, the laws, effects and consequences that are apparent and important to us at our size are still important and determine the nature of things. On the other side things are quite different and we cannot simply reduce the size of our tools or machines to cope. Different things start to happen below the boundary e.g. gravity becomes unimportant, electrostatic forces take over and quantum effects kick in. Another important aspect is that, as particles become nano-sized, the proportion of atoms on the surface increases relative to those inside and this leads to novel properties. It is these “nano-effects”, however, that ultimately determine all the properties that we are familiar with at our “macro-scale” and this is where the power of nanotechnology comes in – if we can manipulate elements at the nanoscale we can affect the macro-properties and produce significantly new materials and processes.

“Nanotechnology is an enabling technology that allows us to develop materials with improved or totally new properties”

What then does something like nanotechnology – a fundamentally high-tech endeavour, have to offer such an apparently low tech and conservative field such as construction? The fact is that construction deals with high-tech materials and processes that have been commoditized for use in the never-ending prototyping that is construction. For example, concrete and steel (together with its bolting and welding) are both high tech materials that are simple to use and therein lie their beauty. Materials and design therefore, is the first avenue through which nanotechnology can exert an influence; by taking staple construction materials and actually designing them rather than merely applying them in a commoditized way. Knowledge at the nanoscale of the structure and characteristics of materials (otherwise known as characterization) will promote the development of new applications and new products to repair or improve the properties of construction materials. For example, the structure of the fundamental calcium-silicate-hydrate (C-S-H) gel which is responsible for the mechanical and physical properties of cement pastes, including shrinkage, creep, porosity, permeability and elasticity, can be modified to obtain better durability. This report will describe these and other ways in which researchers are working towards the use of nanotechnology in design, construction, monitoring and control. However, a recurring theme in the report is that although the techniques of nanotechnology offer great potential for the improvement of building materials, little consideration is being given to it.

1 What is a Nanoparticle ?

A nanoparticle is a microscopic particle whose size is measured in nanometres (nm). It is defined as a particle with at least one dimension less than 200nm. Nanoparticles made of semiconducting material (material that is between a conductor and insulator e.g. silicon) may also be labeled quantum dots if they are small enough (typically sub 10nm) such that jumps in energy levels occur. The importance of this is that the same material of different sizes can emit different colours when energized with, for instance, UV light. Carbon Nanotubes are a sub set of nanoparticles.

Of all businesses, however, the phrase “there’s plenty of room at the bottom”, coined by Richard Feynman in his seminal speech on nanotechnology in 1959, applies most of all to construction since we have plenty of room at the “top” of our macro-sized business. Some examples of the size of the construction industry are that in the EU it is a €350 bn/yr business which employs 10% of the workforce. Globally, 1m^3 of concrete per year is produced for each person on earth. It is, however, a very fragmented business with 97% of EU construction companies having less than 20 people and this contributes to the low level of R&D (less than 0.25% of production value) in the industry.

“Widespread use (of nanotechnology in construction) might be of course hindered (for) economic reasons but, in my opinion, currently, it is lack of knowledge which does not allow for the many small but possibly extremely useful improvements that nanotech might bring about”

This report sets out to describe, for the construction professional, where nanotechnology is already being investigated or even used in the industry, what the future might hold and what the potential effects of it are in the medium to long term. The scope of nanotechnology (even if confined to construction) is vast and an attempt has been made to sift through the work being done and the future being forecast to represent a readable summary of where nanotechnology stands today in relation to the effects it may have on the industry. The views of 20 researchers and industry professionals are presented (mostly from Europe) in a narrative and in statistical form and the quotes in this report are from the respondent’s written comments, however, only those that agreed to their details being used were quoted.

A general note on the following sections is that proprietary concerns often limited a more detailed description of the work being done in industry.

Nanotechnology and Concrete

Concrete is probably unique in construction in that it is the only material exclusive to the business and therefore is the beneficiary of a fair proportion of the research and development money from industry. The following section describes some of the most promising applications of nanotechnology in construction that are being developed or are even available today. More details are available on concrete than the other materials because much of the research described is performed in universities and research institutes and therefore is in the public domain.

At the basic science level, much analysis of concrete is being done at the nano-level in order to understand its structure using the various techniques developed for study at that scale such as Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM) and Focused Ion Beam (FIB) (box 10, p29). This has come about as a side benefit of the development of these instruments to study the nanoscale in general, but the understanding of the structure and behaviour of concrete at the fundamental level is an important and very appropriate use of nanotechnology. One of the fundamental aspects of nanotechnology is its interdisciplinary nature and there has already been cross over research between the mechanical modeling of bones for medical engineering to that of concrete which has enabled the study of chloride diffusion in concrete (which causes corrosion of reinforcement). Concrete is, after all, a macro-material strongly influenced by its nano-properties and understanding it at this new level is yielding new avenues for improvement of strength, durability and monitoring as outlined in the following paragraphs

Silica (SiO_2) is present in conventional concrete as part of the normal mix. However, one of the advancements made by the study of concrete at the nanoscale is that particle packing in concrete can be improved by using nano-silica which leads to a densifying of the micro and nanostructure resulting in improved mechanical properties. Nano-silica addition to cement based materials can also control the degradation of the fundamental C-S-H (calcium-silicate-hydrate) reaction of concrete caused by calcium leaching in water as well as block water penetration and therefore lead to improvements in durability. Related to improved particle packing, high energy milling of ordinary portland cement (OPC) clinker and standard sand, produces a greater particle size diminution with respect to conventional OPC and, as a result, the compressive strength of the refined material is also 3 to 6 times higher (at different ages).

CO2 emissions from the global cement industry are significant and they are increasing. Global cement production is currently around 1.6bn tonnes/yr, and through the calcination of limestone to produce calcium oxide and carbon dioxide, approximately 0.97 tonnes of CO2 is produced for each tonne of clinker produced. Around 900kg of clinker is used in each 1000kg of cement produced so the global cement industry produces around 1.4 tonnes of CO2 each year. This represents about 6% of the total worldwide man-made CO2 production.

Fly ash not only improves concrete durability, strength and, importantly for sustainability, reduces the requirement for cement, 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 SiO_2 nanoparticles part of the cement is replaced but the density and strength of the fly-ash concrete improves particularly in the early stages. Research into haematite (Fe_2O_3) nanoparticles added to concrete has shown that they also increase strength as well as offering the benefit of monitoring stress levels through the measurement of section electrical resistance.

2 What is Titanium Oxide (TiO_2) ?

Titanium dioxide is a widely used white pigment because of its brightness. It can also oxidize oxygen or organic materials, therefore, it is added to paints, cements, windows, tiles, or other products for sterilizing, deodorizing and anti-fouling properties and when incorporated into outdoor building materials can substantially reduce concentrations of airborne pollutants. Additionally, as TiO_2 is exposed to UV light, it becomes increasingly hydrophilic (attractive to water), thus it can be used for anti-fogging coatings or self-cleaning windows.

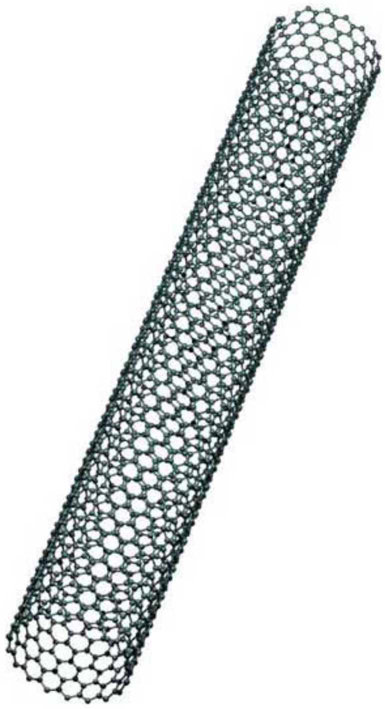
Another type of nanoparticle added to concrete to improve its properties is titanium dioxide (TiO_2) (box 2, p7). TiO_2 is a white pigment and can be used as an excellent reflective coating. It is incorporated, as nanoparticles, in sun-block to block UV light and it is added to paints, cements and windows for its sterilizing properties since TiO_2 breaks down organic pollutants, volatile organic compounds, and bacterial membranes through powerful catalytic reactions. It can therefore reduce airborne pollutants when applied to outdoor surfaces. Additionally, it is hydrophilic (box 4, p9) and therefore gives self cleaning properties to surfaces to which it is applied. The process by which this occurs is that rain water is attracted to the surface and forms sheets which collect the pollutants and dirt particles previously broken down and washes them off. The resulting concrete, already used in projects around the world, has a white colour that retains its whiteness very effectively unlike the stained buildings of the material's pioneering past.

A further type of nanoparticle, which has remarkable properties, is the carbon nanotube (CNT) (box 3, p8) and current research is being carried out to investigate the benefits of adding CNT's to concrete. The addition of small amounts (1% wt) of CNT's can improve the mechanical properties of samples consisting of the main portland cement phase and water. Oxidized multi-walled nanotubes (MWNT's) show the best improvements both in compressive strength (+ 25 N/mm^2) and flexural strength (+ 8 N/mm^2) compared to the reference samples without the reinforcement. It is theorized the high defect concentration on the surface of the oxidized MWNTs could lead to a better linkage between the nanostructures and the binder thus improving the mechanical properties of the composite rather like the deformations on reinforcing bars.

However, two problems with the addition of carbon nanotubes to any material are the clumping together of the tubes and the lack of cohesion between them and the matrix bulk material. Due to the interaction between the graphene sheets of nanotubes, the tubes tend to aggregate to form bundles or "ropes" and the ropes can even be entangled with one another. To achieve uniform dispersion they must be disentangled. Furthermore, due to their graphitic nature, there is not a proper adhesion between the nanotube and the matrix causing what it is called sliding. However, when pre-dispersing the nanotubes with gum arabic an increase in the mechanical properties is achieved, above all in the case of single walled nanotubes (SWNT's). Additional work is needed in order to establish the optimum values of carbon nanotubes and dispersing agents in the mix design parameters.

3 What is a Carbon Nanotube (CNT) ?

Carbon nanotubes are a form of carbon that was first discovered in 1952 in Russia (and mostly ignored) and then re-discovered in the 1990's in Japan. They are cylindrical in shape, as shown in figure below, and their name comes from their nanometre diameter. They can be several millimetres in length and can have one "layer" or wall (single walled nanotube) or more than one wall (multi walled nanotube). The Production cost of nanotubes is high and the price ranges from 20€ to 1000€ per gram depending on quality.



The remarkable properties of CNT's are the cause of intense research around the world on possible applications. For example, they have 5 times the Young's modulus and 8 times (theoretically 100 times) the strength of steel whilst being 1/6th the density. Multi-walled tubes slide telescopically without resistance and they can be ballistically electrically conducting (with no resistance) or semi-conducting depending on the exact structure. Thermal conduction is also very high along the tube axis, but very low perpendicular to it.

The cost of adding CNT's to concrete may be prohibitive at the moment, but work is being done to reduce their price and at such time the benefits offered by their addition to cementitious materials may become more palatable.

4 What is Hydrophilicity and what is Hydrophobicity ?

A material which is attractive to water is hydrophilic and displays hydrophilicity. Conversely, a material that repels water is hydrophobic and displays hydrophobicity.

It is incredible to observe what has been added to concrete in a kind of trial and error assessment of its impact, some examples include sewage and hospital waste, glass and even E. coli bacteria. Although this is part of the drive to produce ecologically efficient concrete, in terms of energy and cement use, and to promote recycling, it is also related to the low tech commoditized nature of construction materials, in they are not designed from a scientific perspective but more experimented with and adjusted empirically. In fact, even some of the rules in structural concrete design are actually empirically derived from observed behaviour. Nanotechnology, involving the study of the fundamental components of concrete can lead the way to a real understanding of concrete construction and service life based on a designed material with predetermined properties. This is strongly related to the study of service life through multiscale modeling (covering multiple dimensional scales such as from nm to m), as discussed in the section on sustainability and the environment. As an example of the kind of additions that have been made to concrete, research has shown that an anaerobic (one that does not require oxygen) microorganism incorporated into concrete mixing water results in a 25% increase in 28-day strength. The Shewanella microorganism was used at a concentration of 10^5 cells/ml and nanoscale observation revealed that there was a deposition of sand-cement matrix on its surface. This led to the growth of filler material within the pores of the cement-sand matrix and resulted in increased strength.

Work is being done along similar lines at the South Dakota School of Mines and Technology to try to develop a biosealant in the form of calcium carbonate excreted from a genetically engineered common soil microorganism. The expectation is that this technique could be used to seal or heal cracks in concrete and results show that the early compressive strength of concrete increases significantly with the increasing concentration of microorganism cells. This has important implications for the durability of concrete and hence sustainability through a reduction of materials use. It is also part of the wider field of “self-healing” materials which encompasses coatings and it is modelled to some extent on the behaviour of natural self-healing or “self assembling” (box 6, p15) processes. In the same vein, autonomic (or spontaneous) self-healing polymers are being developed at the University of Illinois (Urbana-Champaign) which use capsules that break open to fill cracks.

“Concerning the usual corrosion problems in concrete products, nanotechnology can offer smart solutions providing coatings that ‘respond’ to external agents with a ‘response’ that can repair or prevent damage”

As mentioned above, coatings are another area of study for nanotechnology in construction and barrier coatings containing nanoparticles for surface protection of concrete, especially of floors and those for protection against efflorescence are being actively researched. Studies are being conducted on types of nanoparticles in various binders and their effectiveness on the key properties related to concrete deterioration, such as; blocking the transmission of chloride ions, resistance to carbon dioxide, diffusion of water vapour, water uptake, and depth of penetration. So far a solvent containing a low molecular weight epoxy resin and nano-clay particles has shown promising results.

Aggregate is also the subject of research and so called “smart aggregate” is being studied where the elements are cast into the bulk concrete of a roadway and later read by a monitoring vehicle. This is for the moment based on casting micro-electromechanical (MEM) devices (box 7, p16) into the concrete, but an extension of this into the nanoscale envisages “smart nano-dust” that can be sprinkled (or even painted) on the surface or incorporated into the mix to provide wide-scale monitoring in a co-ordinated smart network. Current research activities show that such nanotechnology-based sensors have great potential use in concrete structures for quality control and durability monitoring where these can be designed to 1) measure concrete density and viscosity, 2) monitor concrete curing and measure shrinkage and 3) measure certain key parameters affecting the durability of these structures such as temperature, moisture, chlorine concentration, pH, carbon dioxide, stresses, reinforcement corrosion and vibration. In addition, these sensors have the capability to be powered and interrogated wirelessly or through vibration which could lead to in-built traffic or road condition monitoring. Current research on the application of multifunctional materials such as nanoparticles and carbon nanotubes, shows that, not only do these materials significantly increase the compressive strength of cement mortar specimens (as described above), they also change their electrical properties which can be used for health monitoring and damage detection. The accurate assessment of the in-place strength of concrete using the above parameters can be used to determine whether forms can be removed or not and this can lead to significant savings in both construction cost and schedule.

Self Compacting Concrete (SCC) is one that does not need vibration in order to level off and achieve consolidation. This represents a significant advance in the reduction of the energy needed to build concrete structures and is therefore a sustainability issue. 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 (a material similar to plastic developed using nanotechnology). SCC mixes, which contain a high content of fine particles, need a very effective dispersing system in order to be fluid and workable overtime at low water/cement ratio (high W/C ratios would lead to risk of segregation) and only polycarboxylates can meet these requirements. 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.

Finally, fibre wrapping of concrete is quite common today for increasing the strength of pre-existing concrete structural elements. An advancement in the procedure involves the use of a fibre sheet (matrix) containing nano-silica particles and hardeners. These nanoparticles penetrate and close small cracks on the concrete surface and, in strengthening applications, the matrices form a strong bond between the surface of the concrete and the fibre reinforcement. In the strengthening process pre-cut carbon tows (fibres) and sheets impregnated with the matrix are placed on the prepared concrete surface and bonded using grooved rollers. The ability of the samples to sustain load after cracking is greatly improved by the carbon tows and both the matrix and the interface are durable under wetting and drying and scaling (scraping) conditions. Additionally, there is no decrease in the maximum load capacity after repeated cycles of wetting and drying or scaling.

Nanotechnology and Steel

Steel has been widely available since the second industrial revolution in the late part of the 19th and early part of the 20th Century and has played a major part in the construction industry since that time. A total of 185m tonnes of steel are produced per year in the EU and steel benefits from its wide use in industries which neighbour construction (e.g. automotive) and therefore enjoys a healthy allocation of research funding. The construction industry can benefit from the application of nanotechnology to steel and some of the promising areas currently under investigation or even available today are explored in the following paragraphs.

Fatigue is a significant issue that can lead to the structural failure of steel subject to cyclic loading, such as in bridges or towers. This can happen at stresses significantly lower than the yield stress of the material and lead to a significant shortening of useful life of the structure. The current design philosophy entails one or more of three limiting measures: a design based on a dramatic reduction in the allowable stress, a shortened allowable service life or the need for a regular inspection regime. This has a significant impact on the life-cycle costs of structures and limits the effective use of resources and it is therefore a sustainability as well as a safety issue. Stress risers are responsible for initiating cracks from which fatigue failure results and research has shown that the addition of copper nanoparticles reduces the surface unevenness of steel which then limits the number of stress risers and hence fatigue cracking. Advancements in this technology would lead to increased safety, less need for monitoring and more efficient materials use in construction prone to fatigue issues.

Current research into the refinement of the cementite phase of steel to a nano-size has produced stronger cables. High strength steel cables, as well as being used in car tyres, are used in bridge construction and in pre-cast concrete tensioning and a stronger cable material would reduce the costs and period of construction, especially in suspension bridges as the cables are run from end to end of the span. Sustainabilty is also enhanced by the use of higher cable strength as this leads to a more efficient use of materials.

High rise structures require high strength joints and this in turn leads to the need for 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. When the tensile strength of tempered martensite steel exceeds 1,200 MPa even a very small amount of hydrogen embrittles the grain boundaries and the steel material may fail during use. This phenomenon, which is known as delayed fracture, has hindered the further strengthening of steel bolts and their highest strength has long been limited to somewhere around 1,000 to 1,200 MPa. Research work on vanadium and molybdenum nanoparticles has shown that they improve the delayed fracture problems associated with high strength bolts. This is the result of the nanoparticles reducing the effects of hydrogen embrittlement and improving the steel micro-structure through reducing the effects of the inter-granular cementite phase.

Welds and the Heat Affected Zone (HAZ) adjacent to welds can be brittle and fail without warning when subjected to sudden dynamic loading, and weld toughness is a significant issue especially in zones of high seismic activity. Weld and HAZ failures led to the re-evaluation of welded structural joints in the aftermath of the 1994 Northridge earthquake in the Los Angeles area and current design philosophies include selective weakening of structures to produce controlled deformation away from brittle welded joints or the deliberate over-sizing of structures to keep all stresses low. Research currently under way, however, has shown that the addition of nanoparticles of magnesium and calcium makes the HAZ grains finer (about

$1/5^{th}$ the size of conventional material) in plate steel and this leads to an increase in weld toughness. This is a sustainability as well as a safety issue, as an increase in toughness at welded joints would result in a smaller resource requirement because less material is required in order to keep stresses within allowable limits.

Although carbon nanotubes (CNT's) (box 3, p8) are an exciting material with tremendous properties of strength and stiffness, they have found little application as an addition to steel as their inherent slipperiness (due to their graphitic nature) makes 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 CNT's presents a challenge for their effective use as a composite component.

5 What is a Nano-Composite ?

A nano-composite is produced by adding nanoparticles to a bulk material in order to improve the bulk material's properties.

Two relatively new products that are available today are Sandvik Nanoflex (produced by Sandvik Materials Technology) and MMFX2 steel (produced by MMFX Steel Corp). Both are corrosion resistant, but have different mechanical properties and are the result of different applications of nanotechnology.

Traditionally, the trade off between steel strength and ductility is a significant issue for steel; the forces in modern construction require high strength, whereas safety (especially in seismic areas) and stress redistribution require high ductility. This has led to the use of low strength ductile material in larger sizes than would otherwise be possible with high strength brittle material and consequently it is an issue of sustainability and efficient use of resources. Sandvik Nanoflex has both the desirable qualities of a high Young's Modulus and high strength and it is also resistant to corrosion due to the presence of very hard nanometre-sized particles in the steel matrix. It effectively matches high strength with exceptional formability and currently it is being used in the production of parts as diverse as medical instruments and bicycle components, however, its applications are growing. The use of stainless steel reinforcement in concrete structures has normally been limited to high risk environments as its use is cost prohibitive. However, MMFX2 steel, while having the mechanical properties of conventional steel, has a modified nano-structure that makes it corrosion resistant and it is an alternative to conventional stainless steel, but at a lower cost.

The proprietary nature of the technologies involved in steel manufacture prevents a more detailed description of the exact nature of the nanotechnological aspects of these two products.

<u>Nanotechnology and Wood</u>

Carbon nanotubes (box 3, p8) are a new discovery, whereas wood is an ancient material which has been used since the dawn of civilization. However, perhaps not surprisingly given nature's evolutionary process, wood is also composed of nanotubes or "nanofibrils"; namely, lignocellulosic (woody tissue) elements which are twice as strong as steel. Harvesting these nanofibrils would lead to a new paradigm in sustainable construction as both the production and use would be part of a renewable cycle. 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.

Due to its natural origins, wood is leading the way in cross-disciplinary research and modelling techniques which have already borne fruit in at least two areas. Firstly, BASF have developed a highly water repellent coating based on the actions of the lotus leaf as a result of the incorporation of silica and alumina nanoparticles and hydrophobic polymers. And, secondly, mechanical studies of bones have been adapted to model wood, for instance in the drying process.

In the broader sense, nanotechnology represents a major opportunity for the wood industry to develop new products, substantially reduce processing costs, and open new markets for bio-based materials.

Nanotechnology and Glass

The European glazing market, which represents 45% of the worldwide market, reached a volume of 80,000 units in 2001, at a sales volume of €18bn. The current state of the art in cladding is an active system which tracks sun, wind and rain in order to control the building environment and contribute to sustainability, but this is unreliable and difficult to calibrate and maintain. Consequently, there is a lot of research being carried out on the application of nanotechnology to glass and some of the most promising areas are outlined below as well as some products that are already available.

Titanium dioxide (TiO_2) (box 2, p7) is used in nanoparticle form to coat glazing since it has sterilizing and anti-fouling properties. The particles catalyze powerful reactions which breakdown organic pollutants, volatile organic compounds and bacterial membranes. In addition, TiO_2 is hydrophilic (box 4, p9) and this attraction to water forms sheets out of rain drops which then wash off the dirt particles broken down in the previous process. Glass incorporating this self cleaning technology is available on the market today.

Fire-protective glass is another application of nanotechnology. This is achieved by using a clear intumescent layer sandwiched between glass panels (an interlayer) formed of fumed silica (SiO_2) nanoparticles which turns into a rigid and opaque fire shield when heated.

Most of glass in construction is, of course, on the exterior surface of buildings and the control of light and heat entering through building glazing is a major sustainability issue. Research into nanotechnological solutions to this centres around four different strategies to block light and heat coming in through windows. Firstly, thin film coatings are being developed which are spectrally sensitive surface applications for window glass. These have the potential to filter out unwanted infrared frequencies of light (which heat up a room) and reduce the heat gain in buildings, however, these are effectively a passive solution. As an active solution, thermochromic technologies are being studied which react to temperature and provide thermal insulation to give protection from heating whilst maintaining adequate lighting. A third strategy, that produces a similar outcome by a different process, involves photochromic technologies which are being studied to react to changes in light intensity by increasing absorption. And finally, electrochromic coatings are being developed that react to changes in applied voltage by using a tungsten oxide layer; thereby becoming more opaque at the touch of a button. All these applications are intended to reduce energy use in cooling buildings and could make a major dent in the huge amounts used in the built environment. Further details on this area are covered in the section on Sustainability and the Environment.

Nanotechnology and Coatings

Coatings is an area of significant research in nanotechnology and work is being carried out on concrete and glass (see sections above) as well as steel. Much of the work involves Chemical Vapour Deposition (CVD), Dip, Meniscus, Spray and Plasma Coating in order to produce a layer which is bound to the base material to produce a surface of the desired protective or functional properties. Research is being carried out through experiment and modelling of coatings and the one of the goals is the endowment of self healing capabilities through a process of “self-assembly” (box 6, p15).

Nanotechnology is being applied to paints and insulating properties, produced by the addition of nano-sized cells, pores and particles, giving very limited paths for thermal conduction (R values are double those for insulating foam), are currently available. This type of paint is used, at present, for corrosion protection under insulation since it is hydrophobic and repels water from the metal pipe and can also protect metal from salt water attack.

As well as the applications for concrete detailed in the section above on Nanotechnology and Concrete, there are also potential uses in stone based materials. In these materials it is common to use resins for reinforcing purposes in order to avoid breakage problems, however, these resin treatments can affect the aesthetics and the adhesion to substrates. Nanoparticle based systems can provide better adhesion and transparency than conventional techniques.

In addition to the self-cleaning coatings mentioned above for glazing, the remarkable properties of TiO_2 (box 2, p7) nanoparticles are being put to use as a coating material on roadways in tests around the world. The TiO_2 coating captures and breaks down organic and inorganic air pollutants by a photocatalytic process (a coating of 7000m^2 of road in Milan gave a 60% reduction in nitrous oxides). This research opens up the intriguing possibility of putting roads to good environmental use.

Nanotechnology and Fire Protection and Detection

Fire resistance of steel structures is often provided by a coating produced by a spray-on cementitious process. Current portland cement based coatings are not popular because they need to be thick, tend to be brittle and polymer additions are needed to improve adhesion. However, research into nano-cement (made of nano-sized particles) has the potential to create a new paradigm in this area of application because the resulting material can be used as a tough, durable, high temperature coating. This is achieved by the mixing of carbon nanotubes (CNT’s) with the cementious material to fabricate fibre composites that can inherit some of the outstanding properties of the nanotubes (box 3, p8) such as strength. Polypropylene fibres also are being considered as a method of increasing fire resistance and this is a cheaper option than conventional insulation.

6 What is Self-Assembly ?

Self-assembly is a strategy for nanofabrication that involves designing molecules so that shape-complementarity causes them to aggregate into desired structures in order to reach a point of minimum energy.

The use of processors in fire detection systems which are built into each detector head is fairly well established today. These improve reliability allowing better addressability and the ability to identify false alarms. The use of nanotechnology in the future through the development of nano-electromechanical systems (NEMS) (box 7, p16) could see whole buildings become networked detectors, as such devices are embedded either into elements or surfaces.

Nanotechnology in Sustainability and the Environment

Sustainability is defined as "the ability to provide for the needs of the world's current population without damaging the ability of future generations to provide for themselves". A key aspect of sustainability is conservation through the efficient use of the resources that are tied up in the already built environment. As existing stock increases so will the need for effective maintenance and significant benefits will be offered by a realistic assessment of material lifetimes. Materials scientists have quantitative models which go from nanometres to millimetres and cover 6 length scales (e.g. pore network models to study the permeability of concrete). Engineers have models that go from tenths of millimetres to tens of metres and therefore cover about 6 length scales (e.g. structural analysis). Together they can, theoretically, cover 12 scale lengths and a model covering such a scale would be a powerful tool for service life predictions. This is one of the research areas currently under investigation and part of its advancement depends on the development of computing power which itself is dependent on advances in nanotechnology in the electronics field.

"In the field of cement and its derivatives, sustainability will be a major issue. The control of the cement hydration … could lead to a new generation of products. These products will have a better ratio (of) property to mass, that means, the same or better property could be obtained with less material. Their production processes could be more environment-friendly. The same could be for other construction materials and the components made using them"

Another key aspect of sustainability is the efficient use of energy. In the EU, over 40% of total energy produced is consumed by buildings. Insulation is an obvious solution to reduce some of this energy use, however, limited space for installation is a major problem for building renovation. Micro and nanoporous aerogel (box 8, p17) materials are very good candidates for being core materials of vacuum insulation panels but they are sensitive to moisture. This risk is not acceptable for high performance thermal insulation and the next challenge is to develop a totally airtight wrapping, taking into account the foil and the welding. As a possible remedy, work by Aspen Aerogels has produced an ultra-thin wall insulation which uses a nanoporous aerogel structure which is hydrophobic (box 4, p9) and repels water so it is mould free. Another intriguing application of aerogels is silica based products for transparent insulation, which leads to the possibility of super-insulating windows. Micro or Nano Electomechanical Systems (MEMS or NEMS) also offer the possibility of monitoring and controlling the internal environment of buildings (through a potentially integrated network). This could lead to energy savings much in the way that current motion detectors switch on light only when needed.

7 What is a Micro or Nano-ElectoMechanical System (MEMS or NEMS) ?

MEMS and NEMS are devices which use microfabrication methods to develop moving parts linked to electrical components for detection and action; they are often manufactured in a batch process. MEMS or NEMS generally range in size from a nanometre to a millimetre and at these size scales, a human's intuitive sense of physics do not always hold true. Due to the large surface area to volume ratio, surface effects such as electrostatics and wetting dominate volume effects such as inertia or thermal mass. They are fabricated using modified silicon fabrication and other technologies capable of manufacturing very small devices.

A lot of energy is required to grind clinker into cement and stearic acid (a natural, saturated vegetable oil) can be added to the grinding process to reduce this energy use. This increases cement fineness without a loss of strength, by retarding the caking and agglomeration of the cement during grinding. Saturated oil acid helps grinding without a loss of strength whereas unsaturated oil reduces strength and this is probably due to the oxidation of double carbon bonds in the unsaturated fats by available water. Research has also shown that layered double hydroxide materials (basically stacked molecules which have zones within them for ion exchange) can be used for slow release of admixtures in concrete and therefore increase workability with time. This is a sustainability issue, as the timed release of admixtures can reduce cement usage.

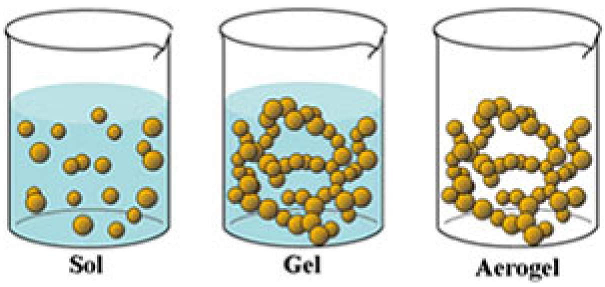
"Nanotechnology is an enabling technology that is opening a new world of materials functionalities, and performances. But it is also opening new possibilities in construction sustainability. On one hand it could lead to a better use of natural resources, obtaining a specific characteristic or property with minor material use. It can (also) help to solve some problems related to energy in building (consumption and generation), or water treatment to mention only a few matters"

Sustainability and environmental concerns are closely linked and clean water is a key sustainable resource. Clean water has been one of the great leaps forward in public health provided by civil engineering and nanotechnology is being used to further this advance. In particular, iron nanoparticles, which have a high surface area and high reactivity are being used to transform and detoxify chlorinated hydrocarbons (some of which are carcinogens) in groundwater. These nano-materials also have the potential to transform heavy metals such as soluble lead and mercury to insoluble forms, thus limiting their transport and contamination. In addition, dendrimers (a regularly branched molecule which resembles a nano "sponge") are capable of enhancing environmental clean-up as they can trap metal ions in their "pores", which can be subsequently filtered out of the water by ultra-filtration. In addition, nano-sized filters for water treatment have been produced which could possibly be applied to geo-environmental remediation though barriers and cut-off walls. These filters can work on both metallic and organic contaminant ions because they have a charged membrane and both the Steric (physical filtration based on its size of openings) and Donnan (filtration based on electrical charge) effects are exploited to filter and collect unwanted contaminants from the system.

"If (nanotechnology) can realistically revolutionize just three or four of the (areas) above (it) will have a major impact on future construction"

8 What is an Aerogel ?

A gel precursor is a chemical or mixture of chemicals that can be activated towards the formation of small (nano-sized) particles suspended in a liquid (a colloid). A wet gel forms when a solution of these dispersed nanoparticle colloids (also called "sols") are induced to form a semi-solid form via condensation.



The solid in the wet gel phase can define a high surface area network of nano-diameter pores that confine the liquid within the structure. An aerogel is directly derived from a wet gel in a process that replaces the entrained liquid with air.

The highly porous nature of the resulting aerogel structure provides a huge amount of surface area per unit weight. It is equivalent to roughly 3 to 5 football fields per gram of solid material – showing that an extraordinary amount of surface is folded in on itself. The percentage of open space within an aerogel structure is about 94%, giving a tortuous path for heat, and this leads to it having the lowest thermal conductivity value of any solid.

Discussion of Survey Results

In order to gain an understanding of the state of knowledge, progress and applications of nanotechnology in the construction industry a survey was conducted of researchers and those in industry. A selection of a 150 individuals and companies was made that represented researchers, engineers, contractors and architects from the EU and worldwide. Many had previously participated in the two Nanotechnology in Construction conferences held in 2003 and 2005 in Paisley, Scotland and Bilbao, Spain respectively.

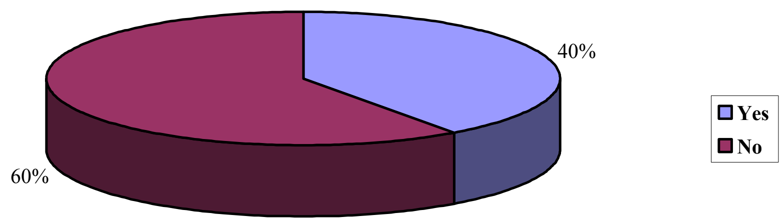
The participants were emailed a questionnaire, a copy of which is included in Appendix B, in mid August and asked to respond before 15^{th} September. Of the 150 people and companies contacted, 20 responded.

Analysis of Survey Responses

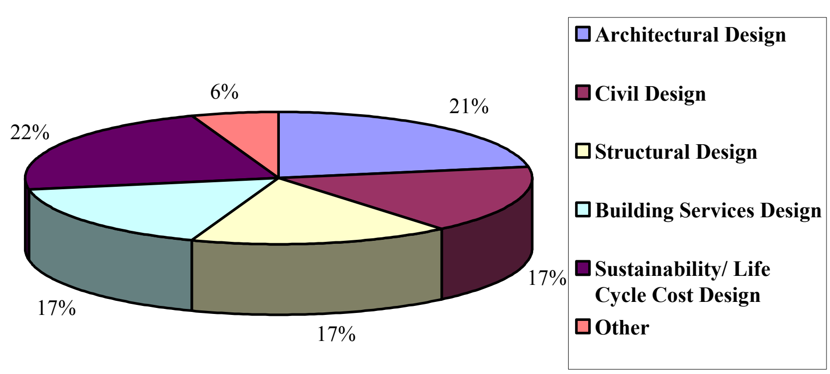
Segment Analysis of Respondents

Respondents were asked about the industry and research segment they were currently involved in. More than one response could be entered and as can be seen in the figures and discussion below, a number of respondents have multiple roles.

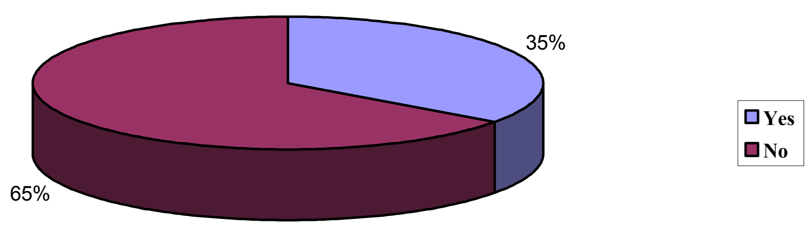
1a Are you involved in design ?



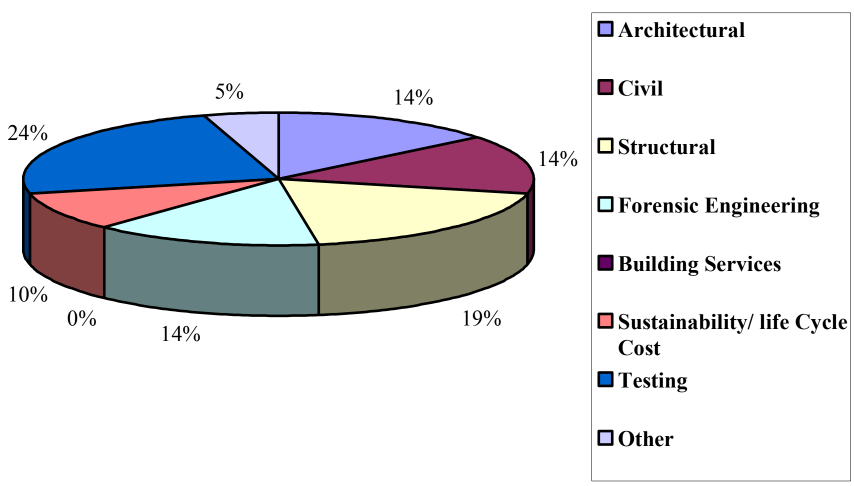
1b Breakdown of Design Area Respondents

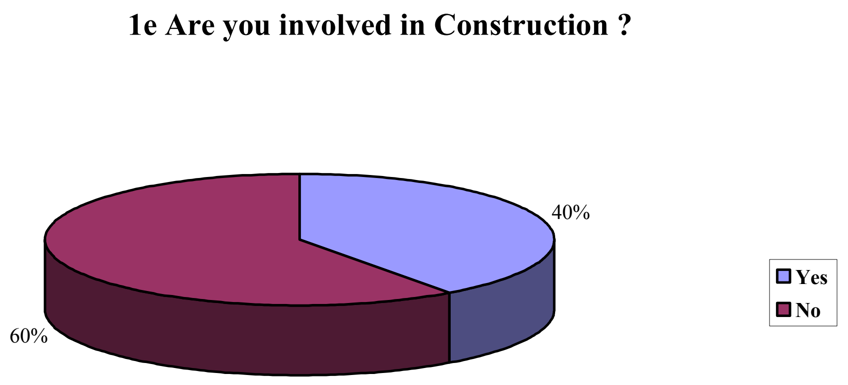


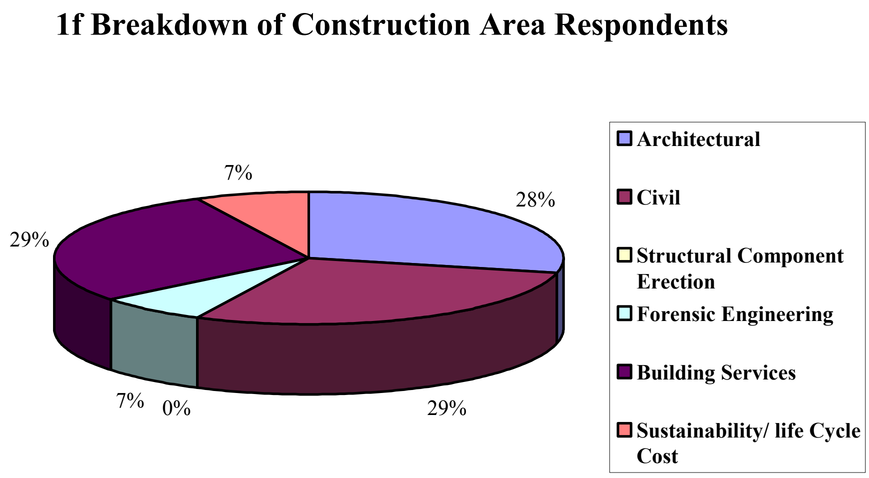
1c Are you involved in Inspection ?

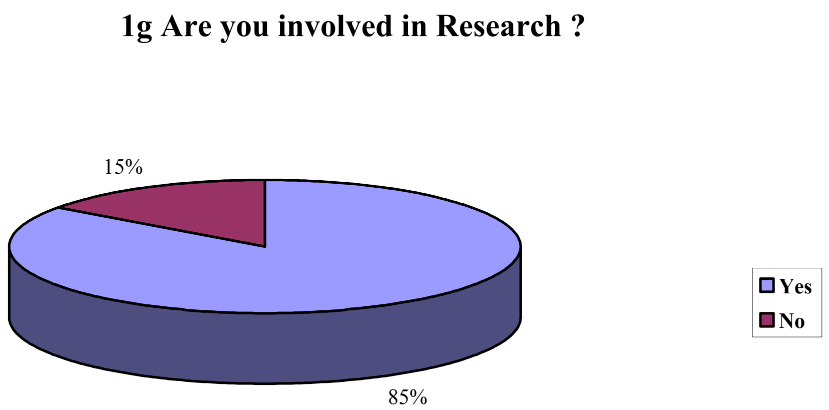


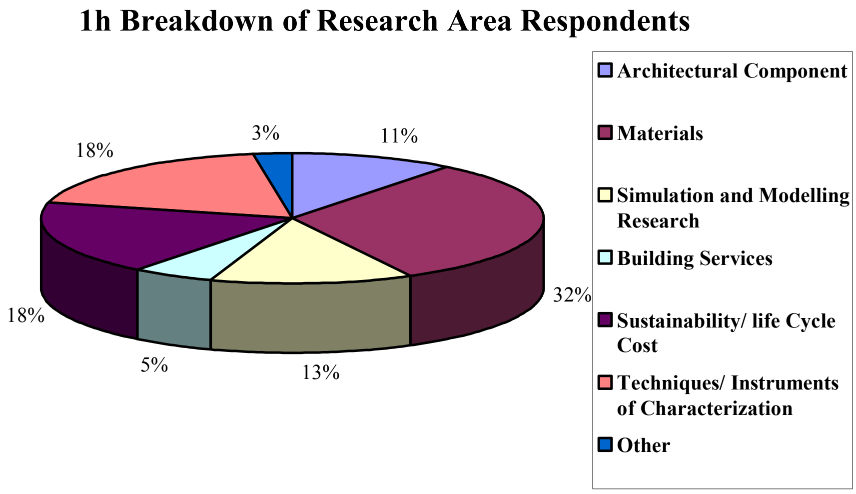
1d Breakdown of Inspection Area Respondents




1e Are you involved in Construction ?
40%
60%
Yes
No


1f Breakdown of Construction Area Respondents
7%
28%
29%
7%
0%
29%
Architectural
Civil
Structural Component Erection
Forensic Engineering
Building Services
Sustainability/ life Cycle Cost


1g Are you involved in Research ?
15%
85%
Yes
No



As can be seen in Fig 1g, a large majority of respondents state that they are involved in research and, as can be seen in the responses included in Appendix A (survey question 1), many come from either universities or government bodies and are researchers. This should be expected since it is those who are in the research and research management field who are most likely to be knowledgeable of nanotechnology in construction and the most willing to talk about it in order to gain recognition for their work. Those in the construction industry itself might be less willing to complete the survey due to time pressures, lack of knowledge or perhaps proprietary concerns, however per Figs 1b, 1d and 1f, those respondents in design, inspection and construction do cover the main areas. A further point to note is that a cross analysis of the respondents' answers reveals that many of the researchers are not solely involved in research, but also work in other fields. Only 13% of the researchers say that are involved in pure research, whereas 23% state that they are also involved in design, 29% say that they are also involved in inspection and 35% say that they are also involved in construction. This is a sign that at least some cross communication is happening between the research community and industry, however, a number of respondents, in their written comments, point out that much more of this is needed.

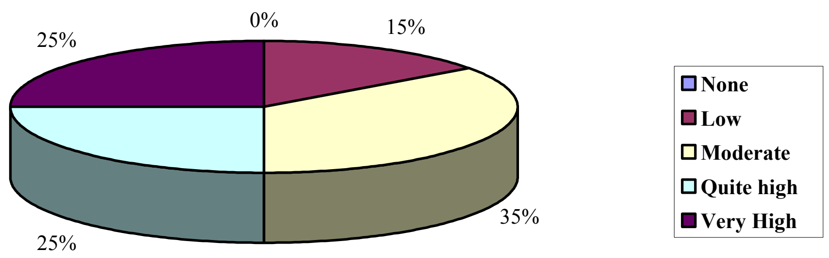
"Bring the academic… experts and industries together for faster development"

As can be see in Fig 1h, a large proportion of the research respondents state that they are involved in materials and this is also to be expected since the manufacture and assembly of construction materials is fundamental to the construction process and any improvements in strength, ductility, durability, cost etc of material would have a huge impact.

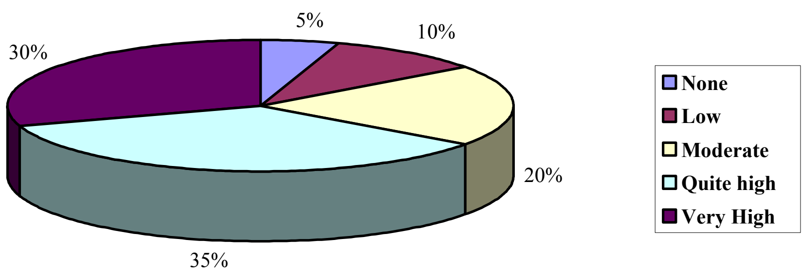
Knowledge of Nanotechnology

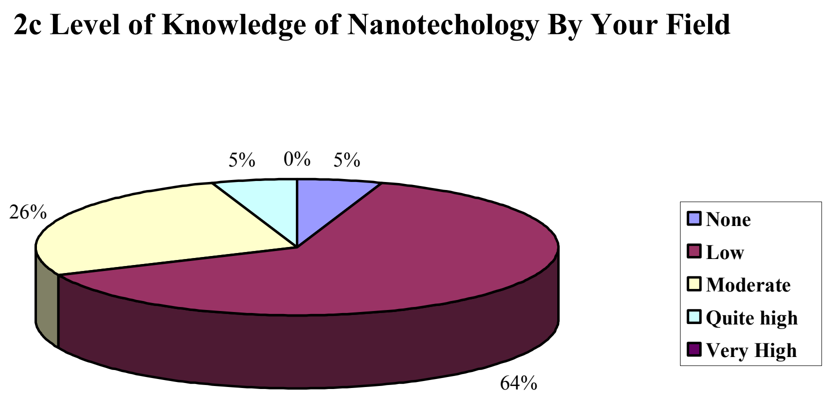
These questions related to the respondent's own knowledge of nanotechnology in general and specifically as regards its applications to construction, as well as their opinion of the profession's knowledge of nanotechnology within their sector or field. As can be seen from the figures and discussion below, there was a wide discrepancy between industry and research.

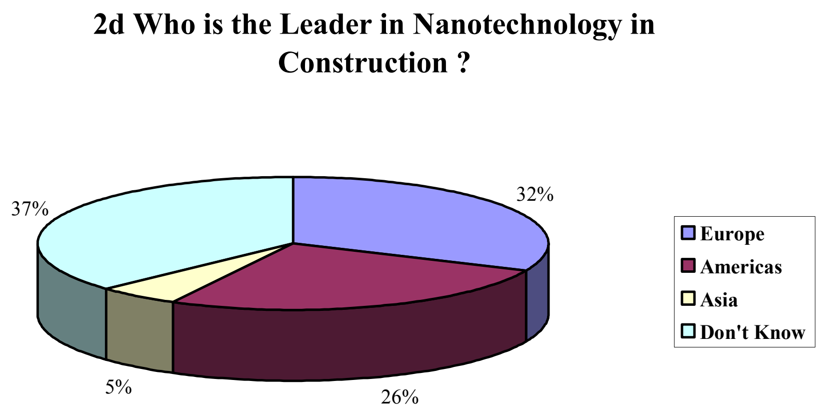
2a Your Level of Knowledge of Nanotechnology in General

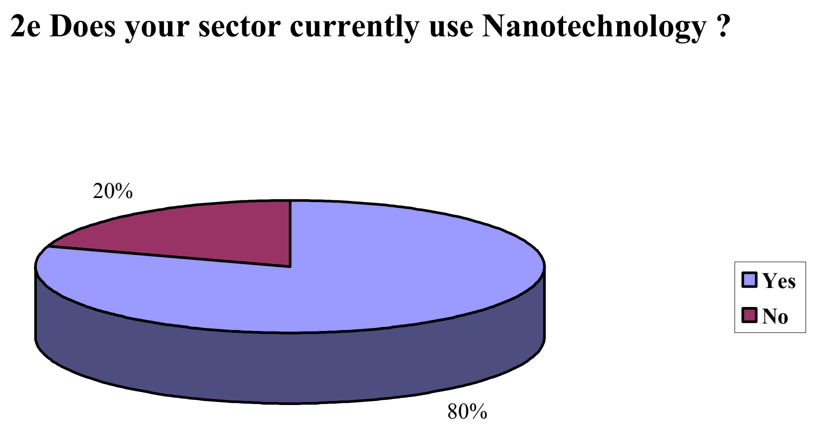


2b Your Level of Knowledge of Nanotechnology in Construction









As can be seen in Fig 2a, the level of knowledge in nanotechnology in general seems quite good, with 60% answering that their knowledge is quite high or very high and only 15% believing it to be low. The level of specific knowledge about nanotechnology applications in construction is higher, see Fig 2b, however, these responses have been skewed slightly by the research slant of the respondents and many (66%) of those from industry had a low knowledge of nanotechnology in their sector and 33% had none. These responses indicate a widespread lack of knowledge in the industry side of construction and many industry respondents even seemed unaware of the term "nanotechnology". This is a significant observation which needs to be discussed and addressed and it is further underlined by the fact that a number of respondents could not identify the global leader in nanotechnology applications for construction, see Fig 2d. This may indicate that, at present, there is no clear leader in nanotechnology in construction or that the applications are not clear.

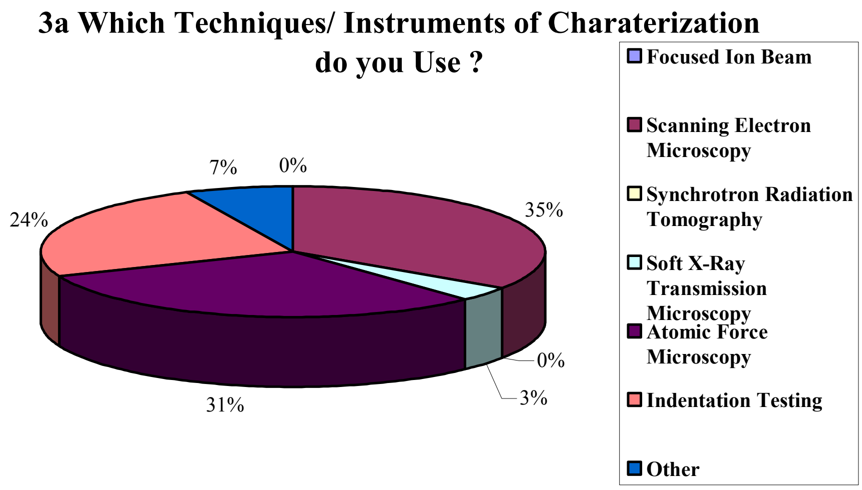
"I can honestly say I do not know what nanotech might do for me, my clients and my projects"

One of the most striking conclusions of the survey, therefore, is the disconnection between research and industry. Despite several promising research projects being carried out, particularly on the materials side, industry seems quite unaware of and disinterested in nanotechnology. This is compounded by the fact that R&D investment is very sparse in the construction area (due to the very fragmented nature of the industry) and that industry and research communicate sporadically. This has led to a lack of appreciation of what nanotechnology can offer the construction industry and also the possibility of having to play catch-up to some other region or supplier that does come up with a break-through.

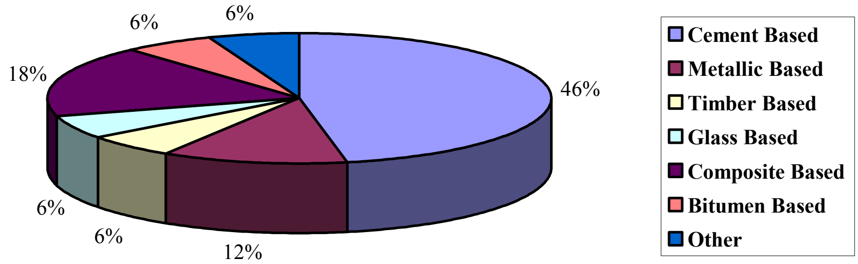
"The inherent advantages (of a nanotechnological approach) need to be appreciated by industry top-level managers (so) as to be incorporated (in) industrial processes … Once there (is) a minimum successful industrial experience, a race to adopt nanotechnology-based products will start"

Current Work in Nanotechnology

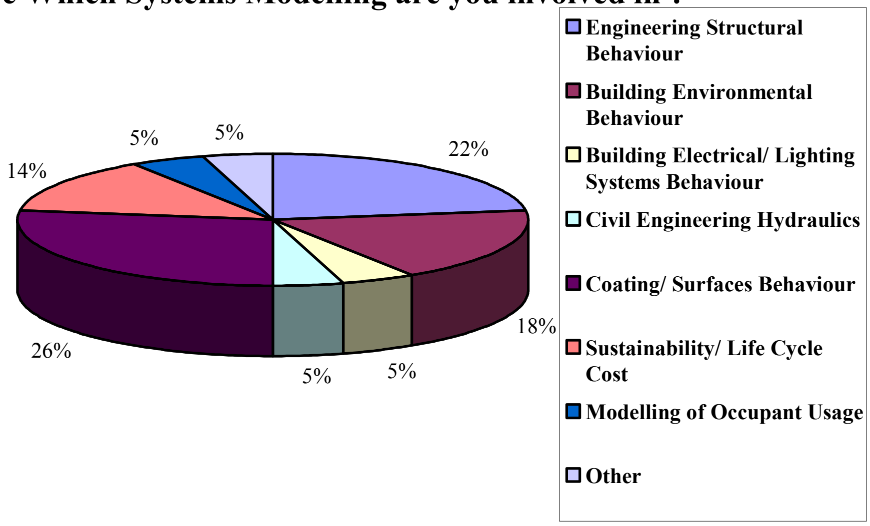
Respondents were asked to indicate the type of work they were currently involved in which included the use of nanotechnology. More than one response could be entered and the responses covered a wide range of instruments, materials, products and applications as discussed below.



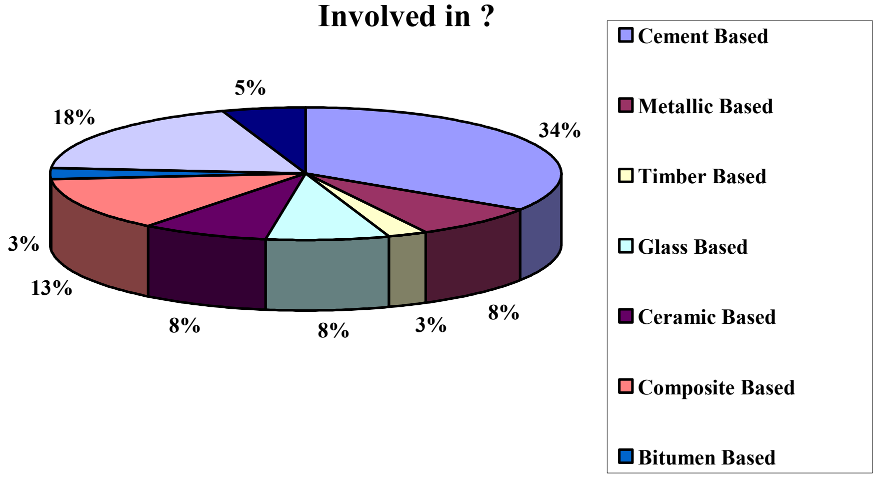
3b What kind of Materials Modelling are you involved in ?



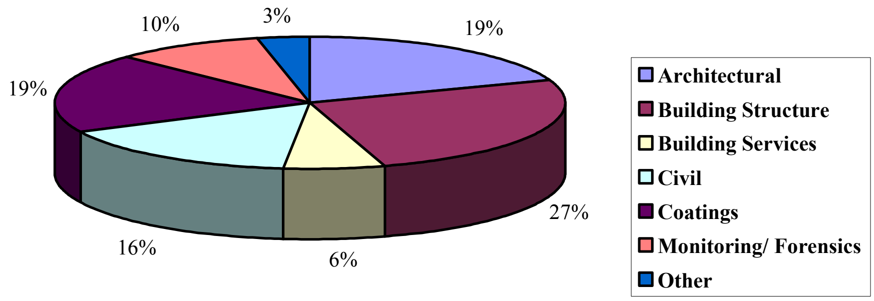
3c Which Systems Modelling are you involved in ?



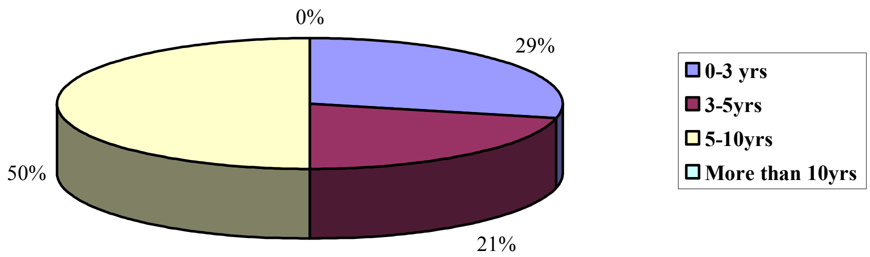
3d What kind of Materials and Products are you Involved in ?



3e What kind of Applications are you Involved in ?



3f How long do you you think before your work will arrive on the construction market ?



As can be seen from Fig 3a, the majority of respondents involved in techniques and instruments stated that they used scanning electron microscopes (35%) and atomic force microscopes (31%). This is to be expected given the nature of nanotechnology and the preponderance of the use of these instruments (boxes 9-12, p27-28) to study materials at the nanoscale. This focus on studying nano-materials is also reflected in the widespread use of indentation techniques for hardness and other property testing. Indentation testing in this regard has the distinct advantage over other methods of being non-destructive.

9 What is an Atomic Force Microscope (AFM) ?

The AFM consists of a microscale cantilever with a sharp tip (probe) at its end that is used to scan the specimen surface. The cantilever is typically silicon with a tip radius of curvature on the order of nanometres. When the tip is brought into proximity of a sample surface forces between the tip and the sample lead to a deflection of the cantilever according to Hooke's law. If the tip were scanned at a constant height, there would be a risk that the tip would collide with the surface, causing damage. Hence, in most cases a feedback mechanism is employed to adjust the tip-to-sample distance to maintain a constant force between the tip and the sample. A recording and interpretation of this force leads to an image being made of the sample surface.

The probe on an AFM can also be also be used to move atoms or manipulate nanostructures.

Respondents indicated that there are several areas which are being studied and researched intensively, see Fig 3d. The main focus of materials and modelling appears to be on cement, composites, glass and metallic alloys, with 34%, 13%, 8% and 8% respectively. Concrete is a staple (if not the staple) material of construction and advances in its properties will have a major impact on industry, hence cement based modelling is an area of particular attention and its nanostructure is receiving (comparably) a lot of research. This is centred around both studying the fundamental calcium-silicon-water reaction at the nanoscale and the addition of nanoparticles to the mix. These particles are either TiO_2 (added to catalyze the breakdown of environmental pollutants), or carbon nanotubes (box 3, p8*)* which are added as a kind of nano-reinforcement. Polypropylene fibres also are being considered as a method of increasing fire resistance and this is a cheaper option than conventional insulation. All these areas are covered in more detail in the discussion above on Nanotechnology and Concrete.

"Nanoscience and Nanotechnology are allowing us to acquire a deeper understanding and knowledge (of) materials and how to correlate structure(s) with their performance"

"In general, the properties of materials depend on their structural characteristics; therefore the knowledge of the structure of materials at a nanoscale is of a great interest"

From Fig 3e, building structure, architecture, environment and coatings seem to be the main focus of nanotechnology in the current work of the respondents (totalling 71%) and architecture will, in fact, be the beneficiary of advances in both coatings and structural applications. However, respondents to the survey felt that coatings were an area that needed more attention at the nanoscale; these included wood, stone, concrete and glass as well as self-healing coatings and polymer based composites for fire resistance.

Another material that is receiving close attention is glass and this is being coated, again, with TiO_2 to produce a self cleaning surface from rain water. This glass, sold by Pilkington amongst others, is one of the applications of nano-coating technology which is available today. More detail on this and the work being carried out on glazing can be found in the section above on Nanotechnology and Glass.

10 What is Focused Ion Beam (FIB) ?

Focused ion beam, is a scientific instrument that resembles a scanning electron microscope. However, whereas the SEM uses a focused beam of electrons to image the sample in the chamber, a FIB instead uses a focused beam of gallium ions.

Much of the work described above is at the development stage and more needs to be done to bring products to market that will have an effect on the construction industry. However, half the respondents thought that the applications of nanotechnology to construction that they are currently working on would arrive within 10 years. Half of these thought that it would happen within 3 years if not already. Given the large proportion of research respondents in the survey, this indicates that some parts of the construction industry may be ignoring applications that will quite quickly be upon them.

The survey also asked what the possible global market impact of the current work might be. Most respondents found this, understandably, to be a difficult question to answer, but many stated that they thought the economic impact would be progressive, but ultimately very significant. The estimates ranged to billions of euros and this is to be expected given the vast material quantities involved and the huge economic footprint of the construction industry; the impact of even minor chemical, physical, or system changes would inevitably be magnified through this economic lens. Indeed, the market is already several billions of euros for high performance ceramic and energy efficient coatings.

11 What is a Scanning Electron Microscope (SEM) ?

In a typical SEM electrons are emitted from a tungsten cathode and are accelerated towards an anode. As the primary electrons strike the surface they are inelastically scattered by atoms in the sample and subsequent emission of electrons are then detected

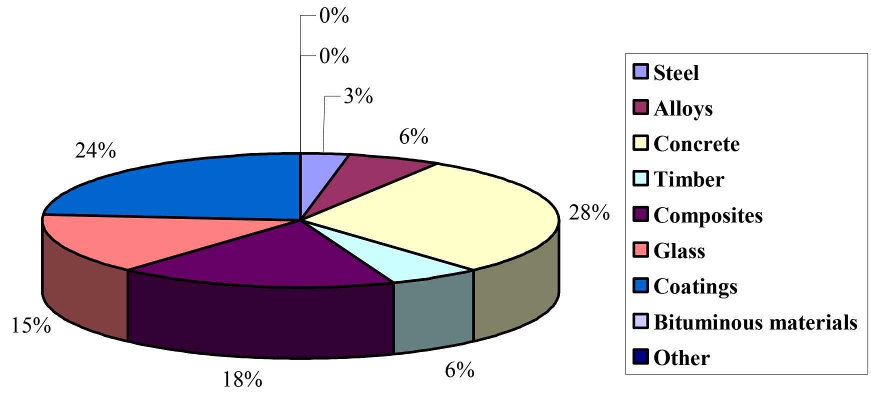
12 What is Synchrotron Radiation Tomography/ Soft X-Ray Transmission Microscopy?

This is the use of electromagnetic radiation to produce images similar to the use of x-rays in medicine. The X-rays are focused to a point and the sample is mechanically moved with the transmitted radiation at each point measured with a detector.

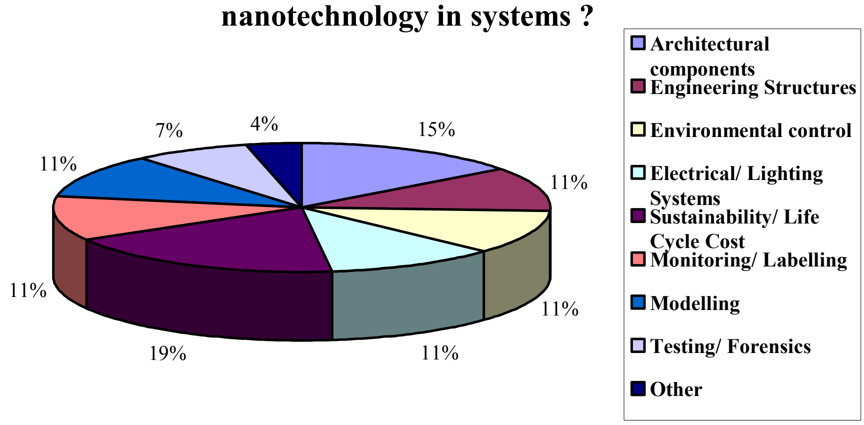
<u>Respondents Thoughts about the Future</u>

The respondents were asked to indicate which materials, systems and sectors they thought would be impacted by nanotechnology in the future. More than one response could be entered and the results are discussed below.

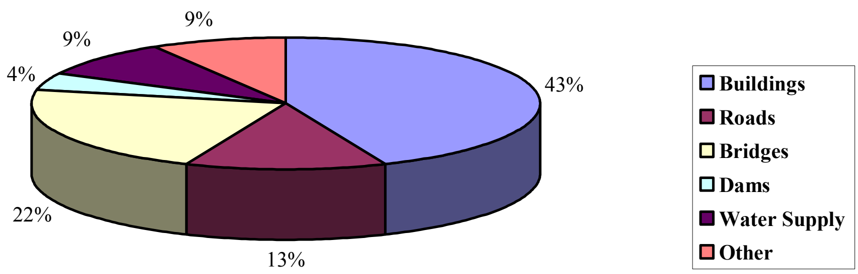
4a What are your thoughts about the future of nanotechnology in materials ?

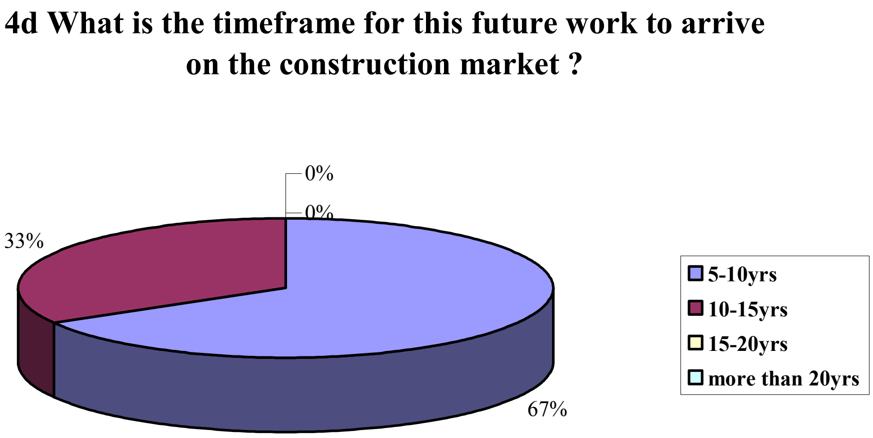


4b What are your thoughts about the future of nanotechnology in systems ?



4c What are your thoughts about the future of nanotechnology in sectors ?





From Fig 4a it is apparent that concrete, coatings, composites and glass are the main materials thought to be affected by nanotechnology in the future with 28%, 24%, 18% and 15% respectively . Concrete is the focus of research on the addition of NEMS or MEMS (box 7, p16) or "smart aggregates" to mix materials in order to gain information on the state of stress or other matters within the structure. In this way, concrete is expected, to become an active rather than passive responder to the environment. In addition, NEMS or MEMS are being studied as a way to monitor structures or buildings on a wide scale for environmental, security or fire issues and, through intercommunication, to produce an intelligent responsive network (covered in more detail in the section on Nanotechnology and Concrete above).

Respondents commented that they thought Chemical Vapour Deposition (CVD) was currently limiting coatings for glass to metal oxide films and they anticipated future developments would allow other materials to be deposited, leading to new products. Respondents also thought that research on coatings would lead, in the future, to corrosion resistant and even self-healing surfaces for steel products.

Nanotechnology is also anticipated to alter the bulk glass material as well coatings and this holds the possibility of future glazing systems selectively tuning out certain wavelengths of light. This could mean significant effects for the environmental control and heat gain of building interiors. In fact, this is part of the reason the majority of respondents seemed to indicate that buildings were the most likely to be affected by nanotechnology in construction.

Nanotechnology is anticipated in the future to enable "multi-scale modelling" that is, the design of materials from the atomic (nano) scale right up to the macro-scale of everyday use and it is this that offers the possibility of designing materials rather than the empirical approach that has been used so far. Nanotechnology, in general, is thought of as a way to improve the properties of conventional materials. thereby directly reducing resource requirements, and as a way to directly and indirectly reduce emissions of, for example, carbon dioxide in cement production. The increased strength and durability offered by nano enhanced materials is fundamentally a sustainable benefit since it enables a more efficient use of resources. More details on this aspect can be found in the section on Nanotechnology in Sustainability and the Environment.

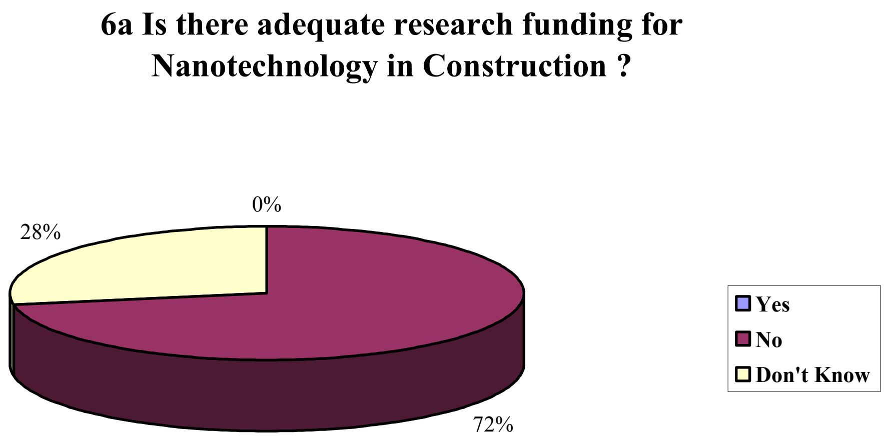
The logical conclusion of the research being conducted on materials is that, as well as buildings, the other areas of engineering structures and architecture likely to be affected in the future are roads and bridges, and this was indicated by the respondents.

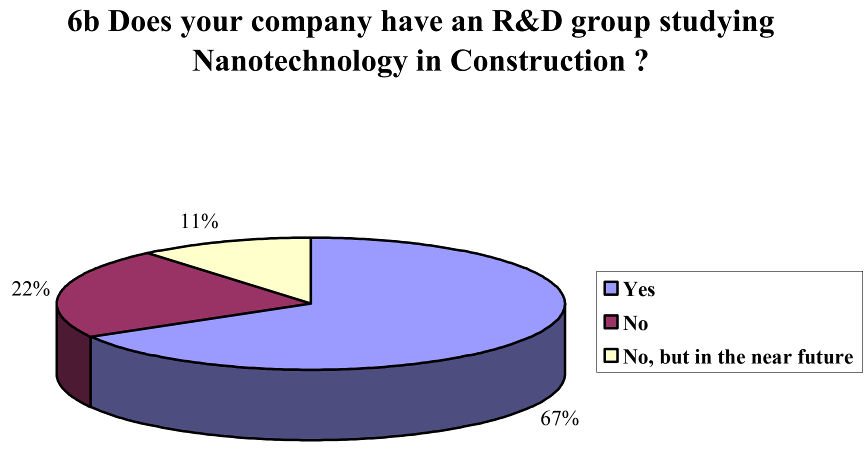
The survey also asked what the possible global market impact of the future applications of nanotechnology in construction might be. Although difficult to predict, estimates ranged to billions of euros and this is to be expected for the same reasons covered in the section above on current work. One respondent commented that they thought the economic impact would extend to the entire cementitious and polymer industries.

Most respondents (67%) believed that this future work would impact the construction industry within 5-10 years and the timescale fits with the research intensive nature of the technology. However, 10 years is close enough that the commercial implications for industry cannot be ignored and the construction business should be looking at these changes sooner rather than later. At the moment, 4 million tn/yr of TiO_2 pigment are produced globally and there seems to be no reason for production not to increase to meet the demands of the ever widening field of application in construction. In contrast, only 65 tn/yr of carbon nanotubes are produced currently worldwide and only a 60% growth in production is predicted in the next five years. It is believed that prices will remain too high for widespread use of carbon nanotubes in construction, despite dropping significantly from their current 20€ to 1000€/gram. Expensive, small scale production of nanotubes as well as clumping, lack of binding to the bulk material, and temperature effects are therefore key barriers to their application in the industry. Barriers to further applications of nanotechnology to glass are the lack of non-metallic CVD coating techniques mentioned above as well as a deficiency of large scale nanoparticle deposition processes which can be integrated with existing ones at atmospheric pressure.

<u>Resources for Research</u>

Respondents were asked about the level of research both in the industry as a whole and in their own companies and the results are discussed below.





This answer to whether there is enough research funding in nanotechnology is an emphatic "no" and this fits with the very low level of R&D in construction in general. Although most answered "yes" to whether there was an R&D group studying nanotechnology in their company this was due to the research slant of the respondents. Apart from materials suppliers such as Lafarge and Pilkington, from the survey responses, there appear to be few commercial construction related companies which have an R&D group studying nanotechnology applications.

"In many markets around the world structural construction is quite a low tech activity. The industry, driven by life safety, is naturally quite conservative. Add to this the fact that buildings are often only a small percentage of the cost of an operation compared to the costs of the activities that go on inside it during its life span. As a result it is often seen as the safest (perhaps read easiest) option to go with the known proven systems. Resistance comes from the risks and unknowns perceived by adopting a new approach, and fear of the implications these may have"

So what holds nanotechnology back? Apart from the factors mentioned in the introduction of a fragmented and conservative business, cost or more accurately cost-to-benefit is a major concern. Carbon nanotubes at the moment are priced at 20 to 1000 €/gram depending on quality and this cost is simply incompatible with the 12bn tonne/yr concrete industry. This issue also touches on the topic of scalability, for even those processes, e.g. nano-vapour deposition, that might look promising in research may be difficult or cost prohibitive to do on an industrial scale. Furthermore, some of the nanotechnology research has no immediate practical application to construction and this is certainly a factor that holds back research spending. Something that is lacking and could certainly help in this regard, is greater communication between researchers and industry, and this is mentioned by many of the respondents to the survey.

"Nanotechnology is absolutely interdisciplinary… up to now research teams have been mainly composed of specialists on a single discipline or research field … Investment on new production processes is a serious drawback, especially for early adopters"

Given nanotechnology's interdisciplinary nature, work across fields such as business, architecture, engineering, biology, chemistry and physics is also especially important and this is something that is lacking and needs to be addressed if nanotechnology, not just in construction but more generally, is to progress to the future that is hoped for it.

"At this moment the main limitation is the high costs of nanotechnology. Also concerns with the environmental and health effects"

Finally, respondents thought strongly that health and safety issues need to be addressed regarding nanotechnology in the environment in general and that this, together with any necessary regulations, may be the ultimate bottleneck in the adoption of nanotechnology in construction.

Conclusion and Recommendations

"The results in terms of product added value, obtained through (the) nanotechnology approach, could not be obtained by conventional approaches (as) they are mature and any minor improvement could be very expensive. In this sense nanotechnology has a disruptive character (and) its results can not be obtained (in) a conventional way. This is the strong point of Nanotechnology. In some way nanotechnology … will be one of the bases of the knowledge-based economy"

In conclusion, nanotechnology is disruptive and offers the possibility of great advances whereas conventional approaches, at best, offer only incremental improvements. Nanotechnology is not exactly a new technology, rather it is an extrapolation of current ones to a new scale and at that scale the conventional tools and rules no longer apply. Nanotechnology is therefore the opposite of the traditional top-down process of construction, or indeed any production technique, and it offers the ability to work from the "bottom" of materials design to the "top" of the built environment. However, many of the advances offered by nanotechnology, be they for economic (carbon nanotubes cost 20-1000€/gram) or technical reasons, are years away from practical application, especially in the conservative and fragmented construction business.

"At this moment the main limitation is the high costs of nanotechnology. Also concerns with the environmental and health effects"

What effects then will nanotechnology have on the day to day work of the average person in the construction industry right now? None. So is it safe for the industry to ignore nanotechnology? Absolutely not; as well as the work performed in construction, nanoscale research is being carried out in every sector of industry from medicine to aerospace and it is, by its nature, interdisciplinary and inter-connected and will therefore cross traditional boundaries in unexpected ways. The waves of change being propagated by progress at the nanoscale will therefore be felt far and wide and nowhere more so than in construction due its large economic and social presence.

"There are three main issues that might prevent the widespread use of the nanotechnology (1) Lack of vision to identify those aspects that could be changed through its use, (2) Lack of skilled personnel and (3) Level of investment"

However, the potential effects of nanotechnology on construction are largely unknown to the construction profession in general, even though specific research is being carried out all over the world in universities and other institutes. These provide pointers to what will soon be available to industry. Many of these advances are due to arrive within the next 5 years and in order to fully benefit from this new industrial revolution, a concerted effort is needed to overcome the key barriers of lack of knowledge and conservatism in construction regarding nanotechnology. Nanotechnology is a complex and deep subject and it is next to impossible to grasp for those who are not actively involved, therefore, awareness of research done can only be increased by educating both students and professionals through easily digestible information made available through universities, relevant institutions, journals and other sources. Respondents to the survey indicated that more emphasis needed to be given to developing a multi-level bottom up approach to solving problems at the macro scale and that this would then lead naturally to nanotechnological solutions. In fact, one respondent characterized this as a problem of the “handshake” between the nano and macro scales. Fundamentally though, much more research funding is needed for construction and in order to fully capitalize on it, increased interdisciplinary working between researchers and communication between those researchers and industry. Two respondents to the survey thought that more needed to be done to develop the tools to modify concrete at the nanoscale rather than “simply” study it (although this was also something that needed more research) and this is surely partly the result of a lack of involvement or interest from industry. Industry needs to have input in research in order to guide it to the practical applications that it desires and this “self-interest” will also encourage industry sponsorship and help to break down the barrier of conservatism.

“Essentially, (there is a) lack of knowledge in material physics and chemistry in the curriculum of civil engineers”

“Nanotechnology in concrete like materials seems to be dedicated rather to testing, observing the nature, than to modifying it”

“Bring the academic... experts and industries together for faster development”

Looking further ahead, much has been written on the potential that may be on offer if all the possibilities of nanotechnology come to fruition. Some of these ideas include “intelligent buildings” where the sensors and integrated control of the building give them self monitoring and management abilities or even “self assembling buildings”, where the materials have become smart enough to build a project simply by being piled together. Some people have even written of such projects having their own “civil rights”. These concepts relate to the idea of “nanobots” or nanometre sized machines that operate rather like the proteins and DNA of living organisms. As can be seen from the above review, such concepts are a very long way off so current engineers and architects need not worry about their jobs going to “miniature builders or assemblers”, but they should be aware of the subtle changes wrought by nanotechnology that could lead to dramatic effects and opportunities at the macro-scale of the built environment.

“Whilst the ability to image individual atoms and manipulate them will excite the few, the real focus now and the near future is rather more prosaic”

One thing for certain is that demographic changes <u>will</u> lead to requirements for the kinds of “intelligent” buildings which can be pre-programmed or re-programmed remotely or autonomously. The aging population, with the concurrent reduction in the number of young people to care for it and the needs of sustainability, mean that development of such smart buildings will be necessary, and nanotechnology, and in particular, nano sensors or “smart dust” (potentially integrated to form a network) will find a huge market in the future. This may be for something as mundane as heating, ventilation, solar shading, alarms or locating and tracking construction materials, or more dramatic such as stress monitoring with structural response. MEMS (box 7, p16) already are in place on the Golden Gate Bridge and are being used to give a real-time, comprehensive strain picture. In any case, progress on this front to the nanoscale will mean a significant change in our relationship with the built environment and its relationship with the natural one from passive to active.

Two areas that appear to be lacking at the moment, in so far as research into nanotechnology in construction, are the use of wood and the environmental control of buildings. Wood is a renewable source of construction materials which has been used for thousands of years and yet, perhaps because of this, work involving nanotechnology is limited to speculation on its benefits (for more details see the section above on Nanotechnology and Wood). The possibilities offered by nanotechnology for the sensing and control of building environment are also the subject of mostly speculation and yet they offer great potential benefits for both comfort and the efficient use of energy. Having said that, there is some research work being done on 'Micro Channel Heat Transfer and Macro Prediction Methods', 'Refrigerant Distribution and Charge Reduction in Microchannel Evaporators and Condensers', 'Microtechnology-based Heat Pumps' and 'Micro Channel Heat Exchangers'. And the further development of these microtechnologies will lead inevitably into the nanoscale.

Finally, the survey respondents strongly indicated that the social, ethical, environmental and health effects of nanotechnology should be openly and thoroughly investigated and discussed. The fear in the general field of nanoscience is that misinformation or misunderstanding in the public arena might lead to reluctance to use nano based products or worse still, legislation banning their use. A little knowledge can be a dangerous thing and it is hoped that this report has been useful in alleviating that issue at least in construction.

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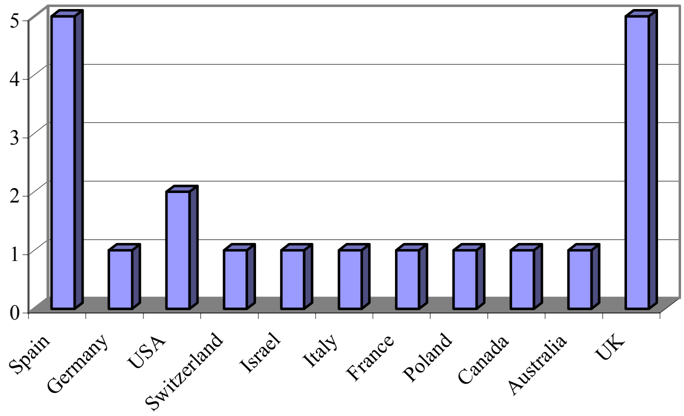
Aerogel, Aspen Aerogels

APPENDIX A

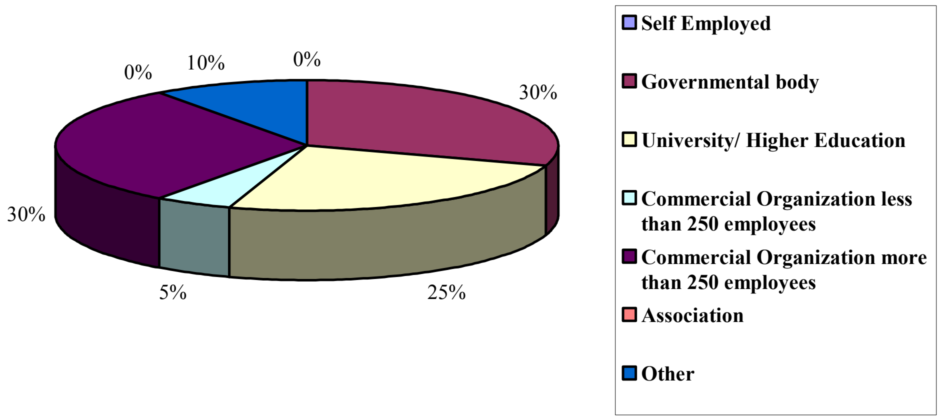
Details of Respondents

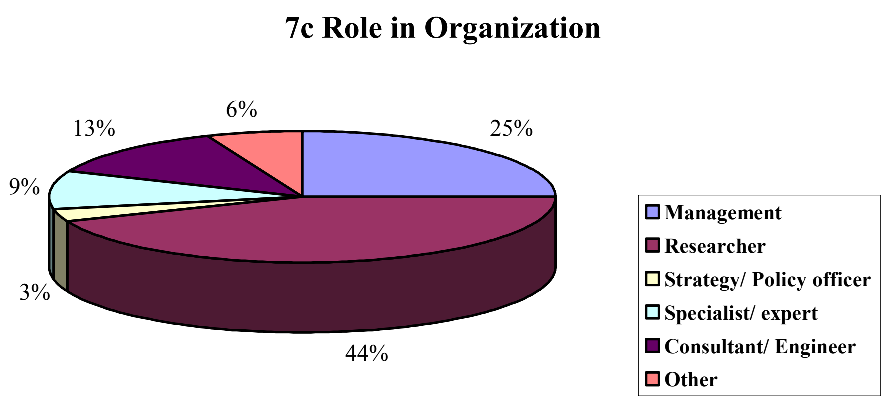
Respondents were asked about their organizations and their roles within them. More than one response could be entered..

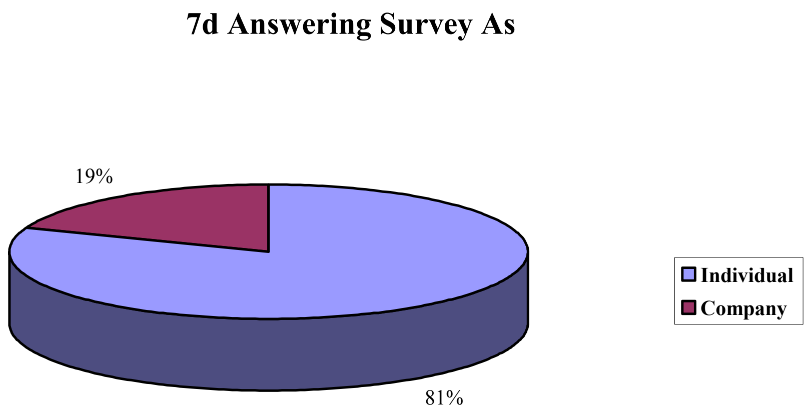
7a International distribution of experts

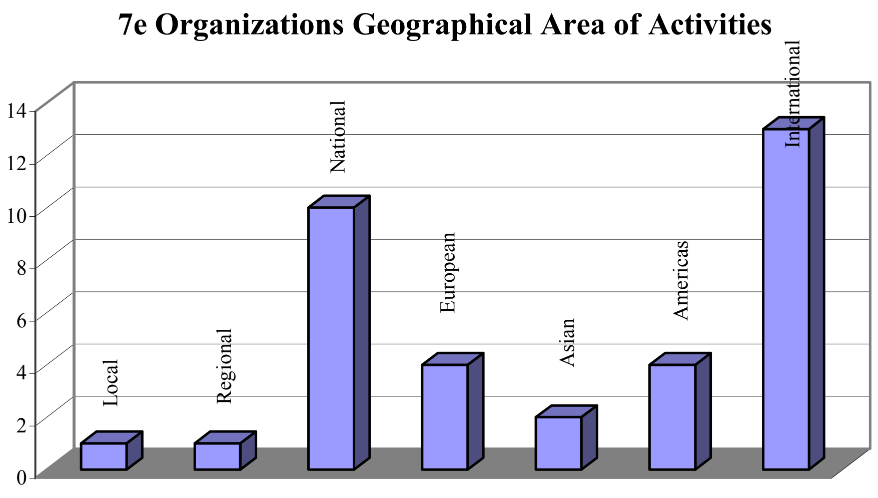


7b Organization Type




7c Role in Organization
25%
44%
3%
9%
13%
6%
Management
Researcher
Strategy/ Policy officer
Specialist/ expert
Consultant/ Engineer
Other


7d Answering Survey As
19%
81%
Individual
Company


7e Organizations Geographical Area of Activities
14
12
10
8
6
4
2
0
Local
Regional
National
European
Asian
Americas
International

These charts show that the majority of respondents (15 out of 20) come from Europe. The survey was targeted mostly to European individuals and companies and additionally there are two Institutes, NANOCOM in Paisley and NANOC in Bilbao, specifically dedicated to studying nanotechnology applications in construction. They also show that the majority of respondents come from either universities or government bodies and are researchers. This should be expected since it is those who are in the research and research management field who are most likely to be knowledgeable of nanotechnology in construction and the most willing to talk about it in order to gain recognition for their work. Those in the construction industry itself might be less willing to complete the survey due to time pressures, lack of knowledge or perhaps proprietary concerns. Most respondents answered that they operated both nationally and internationally and this is typical now of the construction industry that even the smallest firms can operate outside their own areas.

APPENDIX B

Nanotechnology and Construction

Nanotechnology is predicted to be a main driver of technology and business in this century and holds the promise of higher performance materials, intelligent systems and new production methods with significant impact for all aspects of society. On 7th August 2006 Nanoforum and the Institute of Nanotechnology (IoN) commissioned a study of the impact of Nanotechnology on the Construction Industry.

A very important part of the report is gathering the views of a broad range of Industry and Researchers in the field and presenting them in a structured way through the attached survey. We would be grateful for your time in completing this questionnaire.

Please submit your responses by **15th September 2006** - the timing of this exercise is crucial since the completion of the report(s) on Nanotechnology in Construction are due by the end of October 2006 and your input will set the direction of the work. It is important therefore that the views of the construction and research community are taken into account.

We anticipate that the survey, comprising a set of 10 questions, should take on average 15 minutes for you to complete. You are strongly encouraged to participate as this modest investment of your time can have an important impact on future industry and research initiatives in Nanotechnology in Construction. The outcome of the survey will be published on Nanoforum's website (www.nanoforum.org) and you will be first to be informed.

Please email or fax the completed questionnaire back to the address at the bottom.

1. Personal Details

Family name: ……………………………………………………………………………………………….

First name: ………………………………………………………………………………………………..

Email address: …………………………………………………………………………………………..

Organisation:

- Self-employed ☐
- Governmental body ☐
- University/higher education ☐
- Commercial organisation less than 250 employees ☐
- Commercial organisation more than 250 employees ☐
- Association (e.g. trade association, trade union, employers association, chamber of commerce, NGO) ☐

Other (please specify) ……………………………………………………………………………........... ☐

Organisation name (if applicable): ……………………………………………………………………..

Role in organisation:

- Management ☐
- Researcher ☐
- Strategy/policy officer ☐
- Specialist/expert ☐
- Consultant/ Engineer ☐
- Other (please specify) ……………………………………………………………………..☐

Please indicate if you are completing this survey as an individual or on behalf of your company. Individual ☐ Company ☐

Your organisation's country of establishment (indicate your country of residence if answering as an individual person): ……………………………………………………………………

Your organisation's geographical area of activities (indicate your area of activities if answering as an individual)

- Local ☐
- Regional ☐
- National ☐
- European ☐
- Asia ☐
- Americas ☐
- International ☐

2. Industry/ Research Segment Details

2a. Are you involved in Design?
Yes ☐ No ☐
If so, which area(s)? Specify one or more below,

☐ Architectural design

☐ Civil design – please specify below,
- ☐ Roads
- ☐ Bridges
- ☐ Railways
- ☐ Dams
- ☐ Water Supply
- ☐ Other, please specify ……………………………………………………………………..

☐ Structural design
- ☐ Seismic
- ☐ Non-Seismic

☐ Building Services design – please specify below,
- ☐ Environmental Control
- ☐ Lighting
- ☐ Electrical
- ☐ Other, please specify ……………………………………………………………………..

☐ Sustainability/ Life Cycle Cost design

☐ Other - please specify …………………………………………………………………………..

2b. Are you involved in Inspection, Monitoring or Engineering Forensics?
Yes ☐ No ☐
If so, which area(s)? Specify one or more below,

☐ Architectural

☐ Civil – please specify below,
- ☐ Roads
- ☐ Bridges
- ☐ Railways
- ☐ Dams
- ☐ Water Supply
- ☐ Other, please specify ……………………………………………………………………

☐ Structural – please specify below,
- ☐ Seismic
- ☐ Wind
- ☐ Impact
- ☐ Other, please specify ……………………………………………………………………

☐ Forensic Engineering, please specify area ……………………………………………….
☐ Building Services – please specify below
- ☐ Environment Control
- ☐ Lighting
- ☐ Electrical

- ☐ Other, please specify …………………………………………………………………….

☐ Sustainability/ Life Cycle Cost

☐ Testing

☐ Other - please specify …………………………………………………………………………….

2c. Are you involved in Construction?
Yes ☐ No ☐
If so, which area(s)? Specify one or more below,

☐ Architectural component construction, please specify,
- ☐ Internal
- ☐ External

☐ Civil – please specify below,
- ☐ Roads
- ☐ Bridges
- ☐ Railways
- ☐ Dams
- ☐ Water Supply
- ☐ Other, please specify …………………………………………………………………….

☐ Structural component erection

☐ Building Services – please specify below,
- ☐ Environmental control
- ☐ Lighting
- ☐ Electrical
- ☐ Other, please specify …………………………………………………………………….

☐ Sustainability/ Life Cycle Cost

☐ Other - please specify …………………………………………………………………………….

2d. Are you involved in Research ?
Yes ☐ No ☐
If so which area(s)? Specify one or more below,

☐ Architectural component research – please specify …………………………………..

☐ Materials research - please specify below,
- ☐ Steel
- ☐ Alloys, please specify …………………………………………………………………….
- ☐ Concrete
- ☐ Timber
- ☐ Composites, please specify ……………………………………………………………….
- ☐ Glass
- ☐ Coatings, please specify …………………………………………………………………
- ☐ Bituminous materials
- ☐ Other, please specify ……………………………………………………………………….

☐ Simulation and Modelling research – please specify below,
- ☐ Structural, specify below

Seismic Yes ☐ No ☐
Wind Yes ☐ No ☐

- ☐ Hydraulic
- ☐ Transport related
- ☐ Forensics or data acquisition
- ☐ Other, please specify ……………………………………………………………………

☐ Building Services research - please specify below,

- ☐ Environmental control
- ☐ Electrical
- ☐ Other, please specify ……………………………………………………………………

☐ Sustainability/ Life Cycle Cost

☐ Techniques/Instruments of Characterization

☐ Other - please specify ……………………………………………………………………..

2e. In your area(s) of expertise what do you think is the current state-of-the-art, and what are its limitations?

……….

……….

……….

……….

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……….

……….

3. Level of Knowledge/ Involvement in Nanotechnology

	None	Low	Moderate	Quite High	Very High
What would you say is your level of knowledge with regards to nanotechnology in general?	☐	☐	☐	☐	☐

	None	Low	Moderate	Quite High	Very High
What would you say is your level of knowledge with regards to nanotechnology in your sector or field of construction or research?	☐	☐	☐	☐	☐

	None	Low	Moderate	Quite High	Very High
In your opinion, what is the level of knowledge and how advanced are the applications of nanotechnology, within your sector or field of construction or research?	☐	☐	☐	☐	☐

	Not at all	A little	Moderately	Quite a Lot	Very much
How involved in nanotechnology are you/ your company?	☐	☐	☐	☐	☐

	Europe	Americas	Asia	Don't Know
Which world region is the current leader in Nanoscience in Construction (e.g. in terms of scientific publications or use in industry)?	☐	☐	☐	☐

4. Your Current Work

Does your current work or sector of expertise make use of advances in nanotechnology?
Yes ☐ No ☐ (if no, please skip to question 5)

In which of the following fields or sectors are you most active, with regards to nanotechnology applications in construction today?

4a. Techniques/ Instruments of Characterization

☐ Focused Ion Beam
☐ Scanning Electron Microscopy
☐ Synchrotron Radiation Tomography
☐ Soft X-Ray Transmission Microscopy

- ☐ Atomic Force Microscopy
- ☐ Indentation Testing
- ☐ Other – please specify …………………………………………………………………..

4b. Modelling

Materials

- ☐ Cement Based
- ☐ Metallic Based
- ☐ Timber Based
- ☐ Glass Based
- ☐ Composite Based
- ☐ Bitumen Based
- ☐ Other – please specify …………………………………………..

Systems

- ☐ Engineering Structural Behaviour
- ☐ Building Environmental Behaviour
- ☐ Building Electrical/Lighting Systems Behaviour
- ☐ Civil Engineering Hydraulics
- ☐ Coating/ Surfaces Behaviour
- ☐ Sustainability/ Life Cycle Cost
- ☐ Modelling of Occupant Usage
- ☐ Other – please specify ……………………………………………

4c. Materials and Products

- ☐ Cement Based
- ☐ Metallic Based
- ☐ Timber Based
- ☐ Glass Based
- ☐ Ceramic Based
- ☐ Composite Based
- ☐ Bitumen Based
- ☐ Carbon Fibre/ Nanotube Based Materials or Products
- ☐ Other – please specify ……………………………………………………………..

4d. Applications

- ☐ Architectural
  - ☐ Internal
  - ☐ External
- ☐ Building Structure
- ☐ Building Services
  - ☐ Environmental Control
  - ☐ Electrical/ Lighting Systems
- ☐ Civil
  - ☐ Roads
  - ☐ Bridges
  - ☐ Railways
  - ☐ Dams
  - ☐ Water Supply
- ☐ Coatings
- ☐ Monitoring/ Forensics
- ☐ Other – please specify ……………………………………………………………

4e. With regards to the above, describe the work you are involved in and how it relates to the use of nanotechnology in the construction industry

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4f. With regards to the above what are the conventional strategies to solve these problems and how is the nanotechnology approach superior to these strategies?

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4g. With regards to the above, what are the issues that prevent the more widespread use of the nanotechnology strategy rather than the conventional approach?

………..

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4h. With regards to the above, what do you estimate to be the global market value of the construction segment that could be impacted by your work?

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	0-3yrs	3-5yrs	5-10yrs	more than 10yrs
How long do you think before your work in nanotechnology will arrive on the construction market?	☐	☐	☐	☐

5. Your Thoughts about the Future

Which of the following fields or sectors are you most excited about with regards to the application of nanotechnology in construction for the future? If none, please skip to question 6

5a. Materials

☐ Steel
☐ Alloys – please specify ……………………………………………………………………………..
☐ Concrete
☐ Timber
☐ Composites – please specify ……………………………………………………………………….
☐ Glass
☐ Coatings – please specify ………………………………………………………………………….
☐ Bituminous materials
☐ Other – please specify …………………………………………………………………………….

5b. Systems

☐ Architectural components
☐ Engineering Structures
☐ Environmental control
☐ Electrical/ Lighting systems
☐ Sustainability/ Life Cycle Cost
☐ Monitoring/ Labelling
☐ Modelling
☐ Testing/ Forensics
☐ Other – please specify ……………………………………………………………………………….

5c. Sectors

☐ Buildings
☐ Roads
☐ Bridges
☐ Dams
☐ Water Supply
☐ Other – please specify ……………………………………………………………………………….

5d. With regards to the above, describe the relevant concepts or strategies and how they relate to nanotechnology in the construction industry

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5e. With regards to the above what are the conventional strategies to solve these problems and how might the nanotechnology approach be superior to these strategies?

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5f. With regards to the above, what are the issues that might prevent the more widespread use of the nanotechnology strategy rather than the conventional approach?

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5g. With regards to the above, what do you estimate to be the global market value of the construction segment that could be impacted by these concepts or strategies?

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	5-10yrs	10-15yrs	15-20yrs	more than 20yrs
How long do you think before these concepts or strategies may arrive on the construction market?	☐	☐	☐	☐

6. Is there adequate research funding for nanotechnology related to construction?
Yes ☐ No☐ Don't Know ☐

What areas (if any) should receive greater attention?

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7. If your work is in industry, does your company currently have an R&D group studying Nanotechnology in Construction ?
Yes ☐ No ☐ Not yet, but in the near future ☐

9. If you wish to expand on any of your statements or make any other comments, please use the space below

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10. If you feel we should contact someone else in your group or field please pass on the questionnaire to them or indicate the name and contact details below,

………..

………..

………..

Thank you for taking the time to complete this questionnaire.

If you would like to be informed when this report is published, please tick this box ☐
Please tick this box if you agree to us using your personal details in any report ☐

If you have any questions about this questionnaire or the Institute of Nanotechnology, please contact:

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APPENDIX C

Responders to the survey that agreed to their names being used,

Antonio Porro, Labein
Andres Ayela, DIPC
John Roberts, W S Atkins
Janusz Kasperkiewicz, IPPT PAN
Maria Jose Lopez-Tendero, Aidico
Liliana Ravelli, ITCGR
Roland Pellenq, Centre National de la Recherche Scientifique
Sara Goni, IETCC