

# NANOSCALE INNOVATIONS IN CEMENT: A SUSTAINABLE APPROACH FOR FUTURE INFRASTRUCTURE

## Abstract

Over the last decade, there has been remarkable progress in the manufacture and application of all sorts of nanomaterials. This is especially true for nanoparticles, which are now found in practically every area of our life. Construction is a crucial industry that provides building and infrastructure on which all sectors of the economy rely. Though the building industry is conventional, it is evolving by incorporating modern materials and technologies such as nanotechnology. Construction is recognised as one of the top ten nanotechnology applications that will most likely have an impact on people's daily lives. Because construction materials such as cement, concrete, plastic, glass, and steel are utilised in vast quantities, even slight advances at the nano level in materials and processes could result in significant benefits. Concrete is the most frequently used man-made substance, and cement is the principal ingredient; yet, cement manufacture is a highly energy-intensive process that accounts for 6-8 percent of total carbon dioxide emissions that contribute to global warming. Because mechanical strength and performance are governed by the micro- and nano-structure, the use of nanoparticles in cement and concrete may lead to the development of stronger and more lasting concrete structures. With the development of microscopic tools and manipulation at the nanoscale, cement-based materials' chemical reactions, temperature, electricity, magnetism, and other properties can be altered. Rapid industrialization has increased the building industry's growth, putting severe demand on natural resource availability. The environment and sustainability are being negatively tempered by widespread resource exploitation. Therefore, the need is to create new materials with lower energy requirements. The adoption of low-energy production processes and

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the usage of innovative materials with high energy efficiency are also justified by the current energy situation. The use of nanoparticles in multifunctional materials can significantly address this dilemma. The fascinating field of nanotechnology in cement is explored in depth in this chapter, along with its uses, advantages, and prospective advancements in the future.

**Keywords:** Nanofibers, Cement, Concrete, Construction, Nano-Coating, Nano-Composite, Energy efficiency, Nano-sensors

## I. INTRODUCTION

Nanoscience has recently provided considerable scope for linked technology development in a wide range of industries, including a significant impact in the construction sector (Fig. 1). Nanotechnology has evolved as a potent instrument as a result of global advances in nanoscience. The potential benefits of nanotechnology are enormous, posing significant problems and opportunities. Construction is one of the most strategic industries, providing infrastructure for all sectors of the economy. Construction materials such as cement, concrete, plastic, steel, and so on are widely employed, thus the benefits of nanotechnology in construction to society are huge. It is fascinating to analyse an established industry like construction with a contemporary nanotechnological research area because it has a significant economic impact and a low capacity for innovation. Nanotechnology is being applied in the construction industry in many different ways to create cutting-edge materials. It is possible to alter the nano/basic structure of materials using nanotechnology in order to enhance their bulk attributes, such as mechanical performance, volume stability, durability, and sustainability. One of the most desired qualities of nanoparticles in the construction industry is their capacity to provide a mechanical reinforcement to cement-based materials.

Using nanoparticles in building has three main benefits. The first benefit is the ability to produce concrete with an ultra-high strength and increased durability for particular applications. The second benefit is lowering the amount of cement required in concrete to achieve comparable strengths while lowering costs and the environmental effect of construction materials. The third benefit is a shorter building duration because nanomaterials can provide high-strength concrete with a shorter drying time, allowing for quicker construction.

The use of nanomaterials in the building industry may greatly enhance the fundamental qualities of building materials, such as strength, durability, bond strength, corrosion resistance, and abrasion resistance, as well as provide new ancillary features like energy conservation, self-healing, anti-fogging, etc. Essentially, a roadmap has been created for the employment of current building materials like concrete, bitumen, and plastic with nanotechnological elements in the construction of future structures [1]. Fig. 2(A & B) illustrates how the incorporation of nanotechnology into conventional building materials may result in the creation of buildings that are significantly more environmentally friendly, energy-efficient, and sustainable. The advantages and characteristics of nanotechnology in conventional building materials are described in the paragraph that follows.

Significant advances in the construction industry have been made by creating new materials or by enhancing the functionality of already existing ones. Numerous present applications, such as those involving surface coatings, self-cleaning ability, and fire resistance [2], demonstrate this potential. A new generation of customised, multifunctional cementitious composites with superior mechanical performance and durability may be created using nano-engineering techniques. These composites may also have a variety of novel properties, including low electrical resistivity, self-sensing capabilities, self-cleaning, self-healing, high ductility, and self-control of cracks. Because of its enabling properties, nanotechnology has the potential to provide conventional building materials additional functionality, such as eco-innovative solutions. Numerous commercially available products

across the globe show that significant progress is being made in this field [3–8]. It has been well-documented [1, 9–10] to provide an overview of current nanotechnology research in the building sector. Cement, wet mortar, concrete, paints, varnishes, insulating materials, glass, and infrastructural materials have all seen applications of nanotechnology [11–17]. Building materials using nano-sensors and nanoparticulate self-repairing materials are two more recent examples of "smart" advancements [18–19]. Although many nanotechnology applications are still in development, several have already found success on the market. Real-world applications of these technologies as well as potential limitations in buildings have been critically discussed [20–21]. Nanoscale manipulation can alter chemical processes, temperature, electricity, magnetism, and other phenomena. Additionally, the nano alteration may lead to enhancements in ductility, impact resistance, shrinkage, and strength. A new generation of building materials with improved qualities, such as strength and durability, will undoubtedly arise from a better knowledge of the intricate structure of cement-based materials at the nanoscale. When limestone is converted into cement clinker, 0.8 to 0.9 tonnes of carbon dioxide are released into the atmosphere per tonne of cement produced. Therefore, any advancement that may result in lower emissions would have a significant effect on both the economy and environment.

## II. NANOSTRUCTURED CEMENT COMPOSITES

In the same way that computers and electricity are essential to our modern society, so is concrete. In actuality, the construction industry makes great use of it and consumes 6 billion tonnes of it annually. Currently, the average yearly global use of concrete is almost two tonnes per person. Its characteristics have been thoroughly investigated at the macro or structural level, but new developments in microscopy and nanotechnology have generated a lot of interest in the fundamental knowledge of the material at the nano or molecular structural level. Understanding concrete at this new level is opening up new possibilities for enhancing its strength, durability, and sustainability. Concrete is a macro-material that is heavily influenced by its nano-properties. Concrete is a fascinating substance. After mixing water with cement, sand, and aggregates, concrete develops within a few hours and eventually becomes rock-hard. Concrete, the most common substance on earth, is a composite material with a nanostructure and many phases that matures over time. It is made up of bonded water, nano- to micrometer-sized crystals, and an amorphous phase. Concrete exhibits performance and deterioration mechanisms at several length scales (nano to micro to macro), with each scale's attributes deriving from the one below it [22–23]. The "glue" that keeps concrete together, calcium-silicate-hydrate (C-S-H), is an amorphous phase that is also a nanomaterial. A mixture of molecular assemblages, surfaces (aggregates, fibres), and chemical bonds interact to form concrete at the nanoscale through local chemical reactions, intermolecular interactions, and inter phase diffusion. The molecular structure, surface functional groups, bond length, strength (energy), and density are the characteristics of this scale. This scale gives rise to the crystalline and amorphous phase structures as well as the inter-phase borders. The interactions between particles and phases at the microscale, as well as the impacts of working loads and the environment at the macroscale, are defined by the properties and processes at the nanoscale. The engineering characteristics and performance of the bulk material are eventually impacted by processes occurring at the nanoscale [24–29]. The capacity to better understand and engineer the structure of concrete as well as enhance its performance and durability has been made possible by advancements in the characterisation of the nanoscale structure of cement-based materials. It is now obvious that

the crucial structural characteristics of C-S-H and other cement phases exist on the nanometer scale, and that in order to predict and regulate the material's properties and performance all the way up to the macro scale, a fundamental understanding of nanoscale and microscale physical and chemical processes is required. These cement-based materials are the least understood despite their unparalleled significance, ubiquitous presence, and low cost because of the complicated and time-dependent cement hydration process, which begins with the addition of water and aggregates in cement and lasts for several years.

Cement nano-engineering, often known as nano modification, is a rapidly developing area. The creation of innovative superplasticizers, nanoparticles, or nanoreinforcements, as well as other new cement additives, may be accomplished by the synthesis and assembly of materials in the nanometer scale range. Techniques for molecular grafting and hybridization enable direct control over the underlying structure of cement phases. These methods can be utilised successfully in a bottom-up approach to manage the characteristics, performance, and deterioration processes of concrete for better concrete and to provide the substance with new functions and intelligent features that aren't already present. Engineering concrete can be created at the nanoscale in one or more of three places [30]: at solid-liquid and solid-solid interfaces, as well as in the solid and liquid phases of materials. Although the potential for nano-engineering cement-based materials is enormous, there are still a number of issues that must be resolved before this potential can be fully realized. These issues include the proper dispersion of the nanoscale additives, scaling up laboratory results and implementation on a larger scale, and a reduction in the proportion of costs to benefits. Concrete is being extensively analysed at the nanoscale in basic research in order to comprehend its structural makeup. Techniques like Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM), Nanoindentation, etc. are being used. Conventional concrete contains silica ( $\text{SiO}_2$ ) as a regular component of the mix. The use of nano-silica can increase particle packing in concrete, which in turn densifies the micro and nanostructure and improves the mechanical characteristics. This is one of the breakthroughs brought about by the research of concrete at the nanoscale.

Traditional concrete has a variety of fundamental flaws, including sustainability and durability. Concrete buildings consequently experience substantial shrinkage cracking. Furthermore, steel corrosion is causing a lot of concrete infrastructure to age more quickly than is normal. Because chloride and other ions from the environment can enter concrete through pores or cracks and disturb the layer insulating the steel, causing it to rust, reinforcing steel corrodes over time. Understanding the internal structure of concrete and how it affects the characteristics (strength) of concrete is necessary due to the deterioration of concrete constructions. By enhancing the mechanical qualities of the cement paste used as a binder, one can enhance the mechanical properties of concrete. At the moment, admixtures or chemical additives are the main focus of the innovation strategy for contemporary cement-based products. To enhance the physical qualities of concrete, a number of admixtures have been researched. Industry waste items like silica fume, fly ash and blast furnace slag have a "cementitious reaction" and can be added to cement to boost its density and strength or take the place of some of the Portland cement clinker. Such substances have been referred to as pozzolans since antiquity, and the chemical reaction is called a pozzolanic reaction. One innovative method for creating Ultra High-Performance Concrete to address the challenges of sustainability and durability is the use of nanotechnology. In order to lower permeability, which is crucial for extending the service life of buildings and structures, nanotechnology

may be used in the manufacture of concrete. The words "nano-engineering," or "nano modification," have gained popularity and describe the two primary ways that nanotechnology is being used in concrete research [31–33]. With the aid of cutting-edge characterization techniques and atomistic or molecular level modelling, nano-science studies the measurement and characterization of cement-based materials' nano and micro scale structures in order to better understand how these structures affect the materials' macro scale properties and performance. By grafting molecules onto cement particles, cement phases, aggregates, and additives (including nanosized additives) to provide surface functionality, concrete can be nano-engineered by incorporating nano sized building blocks or objects (e.g., nanoparticles & nanotubes) to control material behaviour and add novel properties. Surface functionality can then be adjusted to promote specific interfacial interactions. The cement paste itself, which is made up of several hydration products on a micro scale, is heterogeneous. It is commonly accepted that during the hydration process, calcium silicate hydrate ( $\text{CaO-SiO}_2\text{-H}_2\text{O}$ , abbreviated C-S-H) is formed, which is the cause of the setting and hardening of ordinary Portland cement (OPC). In especially during the early period corresponding to the move from workability to setting, linked with fast variations in kinetics, it is crucial to understand the processes governing its development. Historically, progress in this approach has primarily been made by adding some superfine materials, such as fly ash, silica fume, etc. to cement paste in order to reduce porosity and/or lower the water/cement ratio. The concrete building is now stronger thanks to these additives. The strengthened cement paste's strength, which comes from the hydration products, is the source of the concrete's strength. Researchers are currently looking into different methods for improving cement paste performance by the incorporation of nanomaterials with extremely high specific surface areas. The density of the resulting cement matrix and the kinetics of the reaction are both significantly impacted by the grain size and size distribution of such admixtures. For concretes with greater strength, smaller grain size is beneficial. Nanotechnological advancements have a role in this. Controlling the size, shape, and surface reactivity of nanoparticles is the focus of recent efforts for their synthesis (Table 1; [34–41]). Due to its numerous benefits, such as the ability to synthesise materials at low temperatures, achieve the desired pH for high purity, and regulate the reaction kinetics of the process by altering the reaction mixture's composition, the sol-gel method has been widely used and is a preferred method for the preparation of nanoparticles. A number of additives, including organic acids, surfactants, and electrolytes, can affect the size and form of silica nanoparticles. To enhance the properties of the plastic and hardened material, ultra-fine additives like nano-silica are used in cementitious systems. Silica particles with a size between a micron and a nanometer fill the spaces between cement grains to provide a filler effect. With the correct composition, the higher packing density reduces the mixture's need for water while also enhancing strength since it reduces capillary porosity. Along with this physical consequence, nano-silica exhibits significantly stronger pozzolanic reactivity than silica fume. For the creation and functionality of ultrahigh performance concrete (UHPC), both effects are crucial (Fig. 3). Due to the high surface to volume ratio of ultra-fine particles, the pozzolanic reactivity of quartz powder relies on the particle size. On the nano scale, reactivity is known to rise dramatically with decreasing particle diameters, and nano-silica produced by sol-gel techniques is anticipated to exhibit the similar properties. Coarse quartz particles are known to be virtually non-reactive during cement hydration. By using  $\text{SiO}_2$  nanoparticles, it has been claimed that nanoparticles can reduce the weight of concrete, increase its strength and elasticity, decrease the energy consumption of homes by improving the performance of isolation materials, improve the weathering properties of exterior

surfaces, act as self-cleaning coatings for interior and exterior surfaces, and window glass, purify traffic exhaust for infrastructure projects, and improve polymer's crack resistance. In order to increase concrete's toughness and preserve its whiteness for the duration of the structure, nano-TiO<sub>2</sub> is being investigated. According to one theory, the photo-catalytic activity of TiO<sub>2</sub> breaks down NO<sub>x</sub>, microbes, and organic pollutants [42]. The nano-silica in cementitious systems operates on two levels:

The first is a chemical one: as the pozzolanic reaction between silica and calcium hydroxide progresses, more calcium-silicate-hydrate (CSH) gel is produced. Because nano-silica (n-SiO<sub>2</sub>) is around 100 times smaller than cement, the second function is physical. The residual gaps in the freshly mixed, partially hydrated cement paste can be filled with nano-silica, enhancing the final density.

According to research, using n-SiO<sub>2</sub> can cause a reduction in cement weight of up to 4 kg for every kg of micro-silica added. Different effects can be produced by adding nano-silica to cement paste and concrete. Because it serves as a nucleation site for the precipitation of calcium-silicate-hydrate (CSH) gel, the high surface area of n-SiO<sub>2</sub> is primarily responsible for this working principle. It is still unclear, nevertheless, whether the increased cement hydration in the presence of n-SiO<sub>2</sub> is a result of the substance's high level of surface activity or its pozzolanic activity, or both. Indirect measurements of the viscosity change (rheology) of cement paste and mortars have also been used to determine the accelerating effects of n-SiO<sub>2</sub> addition. The results of the viscosity test demonstrated the need for more water in cement paste and mortar with n-SiO<sub>2</sub> addition in order to maintain the consistency of the mixtures' workability. It was also determined that n-SiO<sub>2</sub> exhibits a stronger tendency for ionic species to bind to it in aqueous media, and the formation of agglomerates is also anticipated. To lessen this effect in the latter scenario, a dispersion ingredient or plasticizer is required. It has also been investigated how the addition of n-SiO<sub>2</sub> affects the cementitious system's water permeability and microstructure. To achieve the same slump time for conventional concrete and n-SiO<sub>2</sub> concrete, several concrete mixes comprising n-SiO<sub>2</sub> particles, fly ash, gravel, and plasticizer have been studied. The test findings demonstrate that adding n-SiO<sub>2</sub> to cured concrete can enhance its microstructure and lessen its water permeability. The mercury intrusion porosimetry studies have proven that adding n-SiO<sub>2</sub> (1-2%) by weight to concrete reduces the relative permeability and pore diameters. Different electron microscope techniques (SEM, ESEM, TEM, etc.) used to examine the microstructure of concrete found that n-SiO<sub>2</sub> concrete had a more homogenous and compact microstructure than regular concrete. In order to increase the density of the interfacial transition zone of aggregates and bond cement paste, n-SiO<sub>2</sub> can react with Ca(OH)<sub>2</sub> crystals to lower their size and number. The n-SiO<sub>2</sub> particles operate as a nucleus to firmly connect with the CSH-gel particles and fill the spaces in the CSH-gel structure. This indicates that adding n-SiO<sub>2</sub> increases the durability of cement pastes by lowering their rate of calcium leaching.

The impact on the mechanical properties of concrete and mortars is the most significant result of the addition of n-SiO<sub>2</sub>. Increased density, decreased porosity, and an improved connection between the cement matrix and aggregates are all effects of adding n-SiO<sub>2</sub>. Concrete made in this way exhibits greater compressive and flexural strength. Additionally, it was discovered that the nature and production method (colloidal or dry powder) affect the n-SiO<sub>2</sub> effect. Even if the addition of n-SiO<sub>2</sub> is reported to have a positive

effect, its concentration will be capped at between 5 and 10%. Increased cracking potential is caused by increased autogenous shrinkage as a result of self-desiccation at high  $n\text{-SiO}_2$  concentrations. High concentrations of the super plasticizer and water, as well as the use of suitable curing techniques, must be used to avoid this result. The fundamental C-S-H reaction of concrete, which is induced by calcium leaching in water, can be controlled by adding nano-silica to cement-based materials. This can also prevent water penetration and increase durability [43–46]. The preparation of silica nanoparticles ( $n\text{-SiO}_2$ ) using the sol-gel method was done in order to compare the mineralogical and morphological characteristics of the calcium-silicate-hydrate gel. The comparative morphological and mineralogical characteristics of cement systems with and without nanoparticles were studied using a variety of techniques, including scanning electron microscopy, powder X-ray diffraction, thermo gravimetric analysis, isothermal calorimeter, etc. Cationic surfactants were used to adjust the size of the nano silica particles. The silica nanoparticle size decreased with the lengthening of the cationic surfactant chain, as shown by the SEM micrographs of the final particles (Fig. 4). In order to synthesise  $n\text{-SiO}_2$  with a diameter of less than 50 nm, the surfactant cetyltrimethylammonium bromide was found to be effective. X-ray diffraction showed that the produced particles are amorphous in nature. Further, silica nanoparticles were added to the cementitious solution to study the comparative mineralogical and morphological characteristics of calcium-silicate-hydrate gel. These studies' experimental findings demonstrated that adding silica nanoparticles up to 5.0% increased cement paste's compressive strength while reducing the setting time of freshly prepared cement paste. The microstructure of cement paste was enhanced by the addition of  $n\text{-SiO}_2$ , and calcium leaching was greatly reduced as a result of the reaction of silica nanoparticles with calcium hydroxide (CH) to create a secondary calcium-silicate-hydrate (C-S-H) gel. In comparison to control cement paste, the compressive strength of cement paste containing 5%  $n\text{-SiO}_2$  is 64% greater after one day and 35% higher after 28 days. TGA study showed that the CH concentration in cement paste containing  $n\text{-SiO}_2$  decreased by 90% after one day and by up to 59% after 28 days. The addition of  $n\text{-SiO}_2$  prevented the formation of needle-shaped crystals of CH, according to the results of microscopic examinations (Fig. 5). Therefore, it may be concluded that nanoparticles can be used to modify the cement's microstructure, resulting in concrete that is more resilient and sustainable.

The electromigration test demonstrated that the addition of nanoparticles and nanoclays increased the mortar's ability to resist chloride penetration, as demonstrated by the decreased apparent chloride anion, DCI, diffusion coefficients for cement mortars made with the same mix design. The value of DCI was reduced by 61.7%, 66.4%, and 76.0%, respectively, when nano- $\text{SiO}_2$ , hydrophilic nanomontmorillonite, and hydrophobic nanomontmorillonite were admixed with fresh cement mortar at 1% by weight of cement. The general ionic permeability of the mortar was also decreased by the nanomaterials, as shown by the reduced Q electric charge flow. Further electromigration test findings showed that the minor addition of nano- $\text{SiO}_2$  and nanoclays significantly increased the cement mortars' resistance to chloride penetration. According to the EIS test, adding nano  $\text{SiO}_2$  to cement mortar greatly enhanced its ionic transport resistance and reduced its electric capacitance [47]. The average chain length of C-S-H gel is increased by nanosilica, according to  $^{29}\text{Si}$  MAS-NMR analyses of cement pastes containing the material. Therefore, it was anticipated that the presence of nanosilica would improve either the quantity or the strength of high-stiffness C-S-H. However, the amount of highly rigid C-S-H gel was greatly



increased by nanosilica. Because high-stiffness C-S-H is more resistant to calcium leaching, this explains why adding nanosilica to concrete has a favourable effect on durability [48].

Due to their strong reactivity, nanoparticles can operate as cement phase nuclei, which further promote cement hydration. They can also serve as fillers, nano reinforcement, and nano reinforcement, which densifies the microstructure and the ITZ and reduces porosity. Effective dispersion is the biggest problem that all nanoparticles face. Even low loadings have self-aggregation issues, which negate the advantages of their tiny size and produce unreacted pockets that could potentially lead to a concentration of stresses in the material. This is especially true for high loadings, but even at low loadings it is a problem. It has been discovered that nano-SiO<sub>2</sub> enhances the workability and strength of concrete [49–51], increases resistance to water penetration, and aids in regulating calcium leaching [52], which is strongly related to many types of concrete degradation. Due to its vast and highly reactive surface area, nano-SiO<sub>2</sub> has also been demonstrated to speed up the hydration reactions of both C3S and an ash-cement mortar [53–54]. Silica fume was shown to be less effective at increasing strength than nano-SiO<sub>2</sub> [55–56]. When 10% nano-SiO<sub>2</sub> was added together with dispersing agents, it was shown that the compressive strength of cement mortars increased by as much as 26% at 28 days, as opposed to just 10% with the addition of 15% silica fume [51]. The strength was seen increase even with the addition of very tiny amounts (0.25%) of nano-SiO<sub>2</sub>, boosting the 28-day compressive strength by 10% and the flexural strength by 25% [49]. It was noted that the production method and conditions for synthesizing the nano-SiO<sub>2</sub> (such as reagent molar ratios, reaction media type, and reaction time for the sol-gel method) affected the outcomes and that the dispersion of the nano-SiO<sub>2</sub> in the paste has a significant impact. In addition to acting as a filler to strengthen the microstructure, nano-SiO<sub>2</sub> also acted as an activator to encourage pozzolanic processes [55].

Concrete can now be cleaned by itself very efficiently with the help of nano-TiO<sub>2</sub>, and it also benefits the environment. Pollutants include NO<sub>x</sub>, carbon monoxide, VOCs, chlorophenols, and aldehydes from automobile and industrial emissions are photo catalytically degraded by concrete that contains nano-TiO<sub>2</sub> [57–58]. In [59], the mechanics of TiO<sub>2</sub>-based photocatalysis are covered in detail. The Jubilee Church in Rome, Italy (Fig. 6), and a 230-m-long stretch of road surfaces outside of Milan, Italy, are two examples of "self-cleaning" and "de-polluting" concrete products that are already being produced by a number of companies for use in building facades and as paving materials for roads and have been used in Europe and Japan. A few studies have demonstrated that nano-TiO<sub>2</sub> can improve compressive and flexural strengths as well as the abrasion resistance of concrete [61–62] in addition to giving concrete self-cleaning qualities [60]. However, it was also discovered that carbonation-induced ageing could lead to a reduction in catalytic efficiency [63].

It has been discovered that nano-Fe<sub>2</sub>O<sub>3</sub> can improve concrete's compressive and flexural strengths as well as give it self-sensing capabilities [64, 51]. The ability of cement mortar containing nano-Fe<sub>2</sub>O<sub>3</sub> to sense its own compressive stress was demonstrated by the volume electric resistance of the mortar changing with the applied load. Due to the lack of integrated or attached sensors, such sensing capabilities are crucial for the building of smart structures as well as real-time structural health monitoring. When Fe<sub>2</sub>O<sub>3</sub> nanoparticles are added, there is a noticeable decrease in all three aspects of water absorption: percentage, velocity, and coefficient at all ages. However, after 90 days of moisture curing, concrete with Fe<sub>2</sub>O<sub>3</sub> nanoparticles has only exhibited a decrease in water permeability. For Fe<sub>2</sub>O<sub>3</sub>

nanoparticles blended concrete, the workability and setting time of fresh concrete have lowered as a result of partial cement replacement with  $\text{Fe}_2\text{O}_3$  nanoparticles. The modulus of elasticity has been found to be greatly increased by nano- $\text{Al}_2\text{O}_3$ . The use of MWCNTs/ $\text{Al}_2\text{O}_3$  composites increased the cementitious system's fracture toughness by 79% and increased its strength by 13%.

The mechanical performance, resistance to chloride penetration, self-compacting qualities, and permeability and shrinkage of concrete have all been proven to be improved by nanoclay particles [65–68]. The nanoscale is where clay and its crucial cement admixture-related qualities occur. Individual, natural clay particles are between micron and submicron in size, and the base structure of clay is made up of crystalline layers of aluminium phyllosilicates with thicknesses ranging from around one nanometer to about two. Genuine nanoparticles are found in exfoliated layers. Recently, it was suggested that PVA (polyvinyl alcohol) might chemically bond to exfoliated clay particles to form linked chains of clay particles. These chains, when added to cement, were found to enhance the material's post-failure qualities [69]. Additionally, it was discovered that unaltered, nanosized smectite clays altered the structure of C-S-H and served as C-S-H nucleation agents [70-71].

The scientific and industrial interest in carbon nanotubes is growing as a result of their unique physical and chemical characteristics. Carbon nanotubes are hollow, tubular channels that might have a single carbon nanotube wall or several walls. Due to their high modulus, tensile strength, and high aspect ratio, CNT have significantly improved the mechanical characteristics of polymer composites. Potential possibilities for usage as nano-reinforcements in cement-based materials are carbon nanotubes and nanofibers. Microcracks that have formed as a result of loading and environmental factors may be crossed by the fibre network, preventing them from spreading and so boosting the mixture's strength and fracture qualities. With elasticity moduli on the scale of TPa and tensile strengths in the range of GPa, as well as unique electrical and chemical characteristics, carbon nanotubes demonstrate exceptional strength [72–74]. Thus, it seems that CNTs/CNFs are among the most promising nanomaterials for improving the mechanical characteristics of cement-based materials and their resistance to crack propagation while supplying such unique capabilities as electromagnetic field shielding and selfsensing [75-76]. Highly structured graphene ring-based materials with single-wall CNTs (SWCNTs), multi-wall CNTs (MWCNTs), and CNFs have extremely high surface areas and very large aspect ratios (of 1000 or more). MWCNTs are multiple, concentric graphene cylinders coaxially organised around a hollow core, whereas SWCNTs are single graphene cylinders. Contrary to CNTs, CNFs have a large number of exposed edge planes along the surface that could serve as favourable sites for chemical or physical interaction. Vapour generated CNFs are more cost-effective than CNTs (approximately 100 times less expensive than SWCNTs [78]) and can be produced in large quantities. Although CNTs/CNFs have undergone significant research in polymeric composites [79–80], their usage in cement has, thus far, been rather modest. Compared to CNFs, CNTs have been the subject of most research projects, which have been carried out on cement pastes [75, 81–85]. The inclusion of CNTs into mortar has only been the subject of a few numbers of studies [76, 85]. The correct dispersion of CNTs/CNFs in cement paste presents one of the biggest obstacles, in part because of their high hydrophobicity and in part because of their potent self-attraction. It has proven to be fairly difficult to include the distinctive mechanical properties of CNTs/CNFs in cement composites, and so far, inconsistent results have been attained. The potential for crack bridging and improved stress

transfer has nevertheless been indicated by the positive interaction between CNTs/CNFs and cement phases that has been seen (Fig. 7). A variety of techniques have been researched to enhance the interfacial interaction by surface functionalization and coating, ideal physical mixing, and/or the use of surfactants while also increasing dispersion and activating the graphite surface. Iron oxide and boron nitride inorganic nanoparticles (BN and Fe<sub>3</sub>O<sub>4</sub>) are used to create nanostructures that influence the microstructure, cement hydration, electrical resistivity, mechanical strength, and other properties. The simultaneous thermal analysis (STA) and concrete resistance gauge (RCON, Giatec) tests showed a considerable improvement in the thermal and electrical conductivity of the composite reinforced with nanostructured BN-F[86].

### **III. IMPROVED DURABILITY AND LONGEVITY**

One of the building industry's long-standing problems, durability, has been solved through nanotechnology. The cement matrix's impermeability and durability against chemical assault can significantly improve when nanoparticles fill up microcracks and voids. Nanotechnology has made substantial advancements in the field of coating, and research is being done on these materials as well as steel, glass, and concrete [87]. Coating creates a layer that is adhered to the base material to create a surface with the appropriate functional or protective characteristics. Nanocoatings can be classified as either having an ultra-thin layer thickness or having inherent functionality, such as utilising the characteristics of unique nanoparticles that are incorporated in a surrounding matrix. Construction uses multifunctional coatings extensively for a variety of purposes, including corrosion protection, thermal insulation, weather resistance, and water proofing. These coatings' performance can be greatly enhanced and improved via nanotechnology. In fact, multifunctional coatings based on nanotechnology are possible. Therefore, the mixing of inorganic and organic components at the nanoscale level in a single material may open up a vast new field of materials research and result in the creation of coatings with multiple functions. Titanium oxide has a high refractive index and a large resultant pacifying power, making it one of the best industrial white pigments. It has a very strong absorption of UV light in addition to flawless transmission of the visible portion of the spectrum. It is a fantastic option for an anti-UV coating due to a gap of the order of 3.4 eV that cuts out UV wavelengths below 365 nm. Concrete structures benefit from extended service lives, which lower repairs and replacement expenses.

### **IV. NANOTECHNOLOGY FOR FIRE DETECTION AS WELL AS MITIGATION**

Polymer nanocomposites, which seem to offer sizable advantages over traditional formulations, have recently emerged as one of the most promising advances in the field of flame retardancy [88]. The utilisation of layered silicates (clay), which has the potential to produce materials with increased flame retardancy and superior physical qualities, has received a lot of attention [89]. They have been the subject of research for the past 20 years or so. The 2:1 phyllosilicates are a structural family that includes clays and the layered silicates that are frequently utilised in nanocomposites [90]. An octahedral sheet of aluminium or magnesium oxide is sandwiched between two exterior silica tetrahedral sheets in their two-dimensional, layered crystal lattice. Depending on the specific silicate, the layer thickness is about 1nm, and the lateral dimensions can range from 30nm to several microns and even larger. The initial discovery was made by Toyota Central Research and

Development Co. Inc. (TCRD), who showed that the adsorption of a monomer with a silane coupling agent between the galleries of the virgin clay might facilitate the production of an intercalated composite [91]. There are currently a lot of options to consider thanks to study in this area. To prepare the nanocomposite, a number of techniques are available. It might use a solution intercalation method [94] or a melt intercalation technique [92, 93]. In-situ intercalative preparation, however, is becoming more popular in this field of study. It has been noted that this nanocomposites' performance boost is quite good and that it is achieved with only a small amount of nanometric filler additions. Usuki, et al. created the exfoliated Nylon 6/clay hybrid for the first time in 1993 by in situ ring-opening polymerizing  $\epsilon$ -caprolactam [95]. It is widely acknowledged that achieving good flame retardant qualities requires the production of a nanocomposite (whether intercalated or exfoliated). For instance, it has been demonstrated in cone calorimeter studies that, in comparison to the unfilled polymer, the peak heat release rate only lowers by 25% for EVA/5% Na-MMT microcomposite and by 50% for EVA/5% Cloisite1 30B nanocomposites [96]. The degree to which clay particles are dispersed in the polymer matrix may significantly affect flammability [97]. Between 2 and 10% of the final weight is the weight ratio. Even other researchers asserted that the weight ratio was 1% [98].

A spray-on cementitious coating frequently provides steel constructions with fire resistance. Because they need to be thick, have a tendency to be brittle, and require the addition of polymers to improve adhesion, current Portland cement-based coatings are not very common. However, because the resulting material can be utilised as a robust, long-lasting, high temperature covering, research into nano-cement (made of nano-sized particles) has the potential to develop a new paradigm in this field of application. In order to create fibre composites that can inherit some of the excellent qualities of the nanotubes, such as strength, carbon nanotubes (CNTs) are mixed with cementitious material. A less expensive alternative to traditional insulation is the use of polypropylene fibres to increase fire resistance.

Today, it is pretty well established that fire detection systems use processors that are integrated into each detector head. These increase reliability, making it possible to manage problems more effectively and to spot false alarms. Future nanotechnology applications could transform entire structures into networked detectors by creating nano-electromechanical systems (NEMS), which are embedded into either elements or surfaces. Despite the fact that this field is young, there is little doubt that it will succeed in the near future due to its special ability to directly interact at the nanoscale. To date, numerous patent applications have been made regarding various polymer-clay nanocomposite synthesis methods [99]. But there are currently just a small number of commercially available goods. Polymeric nanocomposites are a relatively new field, and more research still to be done. Therefore, it is pretty obvious that the scientific community still does not have complete access to the entire knowledge base of nanocomposites. In this area, basic research can unearth a wealth of additional data that will improve our understanding of both processing and application.

## V. SELF-HEALING PROPERTIES & PHASE CHANGE MATERIALS FOR BUILDINGS

The capability of cement with nanotechnology enhancements to self-heal is remarkable. Researchers have created cementitious materials that contain nanoparticles that react with calcium compounds and water to seal gaps on their own. These nanoparticles help the precipitation of healing agents when cracks develop as a result of shrinkage or outside influences, halting further degeneration and prolonging the lifespan of structures. Polymeric materials that can instantly repair cracks are being used in research on self-healing materials. A microencapsulated healing agent and a catalytic chemical trigger are combined with an epoxy matrix to promote spontaneous healing. When a crack appears, a microcapsule bursts and, through capillary action, delivers a healing chemical into the crack plane. Contact with the catalyst causes the healing agent to polymerize, which bonds the fracture faces.

Through the energy embedded in building materials and products, energy used during construction processes, and energy used by building ecosystems, buildings account for more than 40% of carbon emissions. Acute strain is being placed on the resources of building materials as a result of the housing sector's fast growth. The environment and sustainability are being negatively tempered by widespread resource exploitation. Therefore, it is imperative to create innovative materials with lower embodied energy requirements for structures. The adoption of low energy production processes and the usage of innovative materials with high energy efficiency are also justified by the current energy situation. In situ polymerization and miniemulsion polymerization techniques can be utilised to create nanocapsules that are employed as phase change materials (PCM). One of the most practical methods to encapsulate liquid PCMs is the in-situ polymerization process. PCM serves as the outer shell while polymers serve as the inner core. The heat transfer efficiency, heat transfer area, PCM sensitivity to the environment, and volume variations while phase change takes place can all be significantly improved by using nano-encapsulated phase change materials (NEPCMs). NEPCMs are applicable to a variety of fields, including textiles, solar energy storage, and building cooling and heating. N-Tetradecane was employed as the main component, according to Fang G et al. The polymerization of the shell utilised urea and formaldehyde [100]. The core material of nanocapsules was well encapsulated, and their overall size was approximately 100 nm. Constantinescu Nano-composite materials were created by combining epoxy resin, aluminium powder, and a PCM with significant latent temperatures. As PCMs, several polyethylene glycols with molecular weights of 1000, 1500, and 2000 were utilised. Due to their high latent heat, acceptable phase change temperature, and outstanding performance stability, they discovered that PCMs are appropriate for use in construction applications. CuO-oleic acid nanofluids were explored by Harikrishnan et al. as a brand-new phase-change material [101]. CuO nanoparticles mixed in oleic acid and indicated as a superior PCM for cooling thermal energy storage applications range in size from 1 to 80 nm. Miniemulsion polymerization was used to encapsulate n-hexadecane in high molecular weight polystyrene nanoparticles for thermal energy storage. The catalyst used was an ionic liquid (IL) made of imidazolium, which contains iron. By using dynamic light scattering, transmission electron microscopy, gel permeation chromatography, and differential scanning calorimetry, researchers were able to determine the phase change material (PCM)-containing nanoparticles' particle size, shape, molecular weight, and thermal performance, respectively [102].

## **VI. ENVIRONMENTAL SUSTAINABILITY & STRUCTURAL HEALTH MONITORING USING NANO SENSORS**

Nanotechnology has advantages for sustainability in the manufacture of cement. Researchers have lessened the requirement for clinker, a crucial element of conventional cement manufacture that consumes a lot of energy and emits a lot of carbon dioxide, by integrating nanoparticles. Furthermore, nanostructured cement composites frequently require less water during mixing, which lowers the amount of water used in construction. The necessity for sophisticated structural health monitoring and damage detection technologies has become more apparent as people are becoming more conscious of the economic and social implications of ageing, deterioration, and extreme events on buildings in particular and civil infrastructure in general. Over the past three decades, researchers have researched structural health monitoring (SHM) methods based on changes in dynamic features. These techniques can determine if harm has occurred in cases where the damage is significant. However, the current approaches are less effective at early stages of damage. At the CSIR-CBRI, studies are being conducted with the goal of enhancing damage detection techniques through the application of cutting-edge signal processing, novel sensors, and control theory. The loads, environmental conditions, and its behaviour must be closely monitored in order for a building to achieve the requirements of safety, durability, serviceability, and sustainability over its long-term use. Optic fibre sensors, PZT sensors, gauges based on cement, and corrosion sensors are currently common in SHM. There could be hundreds, possibly thousands, of sensors in a SHM system for buildings. Using connected sensors will result in a number of issues, including greater cost, manpower, and decreased data transfer dependability. The new generation wants wireless nanotechnology-based sensors as well as bio-inspired sensing technology and sensors in light of these factors. Cement and epoxy resin are combined with nanomaterials including carbon black particles, carbon nanofibers, and carbon nanotubes to create brand-new self-sensing materials and sensors. Buildings may easily utilise the nano-film and nano-paint based on these materials as a coating with a sensing function.

By adding carbon nanotubes (CNTs), cement's electrical properties were induced. Despite having a poor thermal conductivity that makes it a potential thermoelectric (TE) material, cement's extremely low electrical conductivity prevents practical utilization. As a possible solution, it is suggested that cement composites with trace amounts of CNTs be introduced. Due to their better electrical conductivity and suitability as additives for carbon isotope-based composites, CNTs can enhance the TE performance of cement-based composites. These composite materials are suitable for use as TE structural materials in buildings that capture energy [103]. In order for concrete to be utilized in pavements and structures, where it must resist deformation, penetration, and abrasion, its hardness must be raised. This study investigates how the inclusion of CuO and/or TiO<sub>2</sub> nanoparticles affects the cement's hardness. CuO and TiO<sub>2</sub> nanoparticles have equal impacts on the microstructure and hardness, but when both are added in comparable amounts, the composites display denser microstructures and higher hardness [104].

The development of innovative sensors that could be utilised to realise a distributed sensor network is given a new chance by nanotechnology. Different signals radiated from a structure can be captured by a series of sensors using current advances in nanotechnology.

## **VII. NANOTECHNOLOGY IN SELF-CLEANING MATERIALS FOR CONCRETE AND GLASS**

The lotus leaf has a remarkable capacity for maintaining its own cleanliness and dryness. In our nation, the lotus plant is well renowned for its exceptional cleanliness and is revered as a representation of purity. White pigment titanium dioxide (TiO<sub>2</sub>) is a great choice for reflective coatings. Since TiO<sub>2</sub> oxidises organic contaminants, volatile organic compounds, and bacterial membranes through potent catalytic reactions, it is added to paints, cements, and windows to block UV light and for its sterilising qualities. Therefore, when used on outdoor surfaces, it can lower airborne contaminants. Additionally, because it is hydrophilic, surfaces to which it is applied have the ability to clean themselves. Significant advancements are being made in the materials used in civil construction to reduce maintenance requirements and boost longevity. The ability of titanium dioxide (TiO<sub>2</sub>) added to glass fibre reinforced concrete (GRC) with amounts of 3, 5, and 7% with regard to the mass of cement to self-clean was examined in this study [105].

The majority of glass used in building exteriors regulates the amount of light and heat that enters the structure. There are four main methods being studied by nanotechnological researchers to prevent heat and light from entering through windows. In the beginning, spectrally sensitive thin film coatings for window glass are being produced. These are essentially a passive solution, albeit they have the potential to filter out undesired infrared light frequencies (which heat up a room) and lessen heat gain in buildings. Thermochromic technologies, which react to temperature and provide thermal insulation to give protection from warmth while keeping appropriate lighting, are being researched as an active solution. Photo chromic technologies, which are being researched to increase absorption in response to variations in light intensity, are a third technique that achieves a similar result through a different process. And finally, electro chromic coatings that change in transparency at the push of a button in response to variations in applied voltage are being developed. All of these applications aim to cut down on the enormous quantities of energy consumed to cool buildings, and they might significantly lower that amount [106].

## **VIII. NANOTECHNOLOGY IN WOOD&STEEL**

As a green fabric, wood is broadly utilized in building enrichment, railroad development, and other areas. In any case, the wood itself has characteristic absconds of being simple to retain water and distort, spoil, and diminish in quality. The physical and mechanical qualities and solidness of fake fast-growing timberland wood are indeed more regrettable. As wood alteration can make strides the dimensional solidness, strength, quality, and other properties of wood, it has been broadly utilized. Chemical alteration is the most strategy of wood adjustment. The advancement of nanotechnology has brought more conceivable outcomes for wood adjustment [107]. Wood is a traditional building material, but it also contains "nanofibrils" or nanotubes, which are lignocellulosic (woody tissue) components that are twice as strong as steel. Since both the manufacturing and the utilisation of these nanofibrils would be a renewable cycle, harvesting them might result in a new paradigm for sustainable building. In terms of UV absorption and penetration, using nanotechnology in the production of wood coatings is a significant innovation. Despite the fact that wood is naturally sturdy and resilient, exposure to the elements can harm not just its physical qualities but also its aesthetic appeal. Nanoscale UV absorbers have special

advantages in preventing UV radiation from deteriorating coatings and coated substrates. Due to the particles' small size, large levels of protection can be provided without impairing the impregnation's transparency. The lifetime of the coating will be extended by the use of nanoscale UV absorbers, which will shield the wood substrate from UV radiation that damages wood.

The severe outside conditions are where these items are most intriguing. Adding functionality to lignocellulosic surfaces at the nanoscale, according to some researchers, may create new possibilities for lignocellulosic products that include electronic components, self-sterilizing surfaces, and internal self-repair. These unobtrusive active or passive nanoscale sensors would monitor structural loads, temperatures, moisture content, decay fungus, heat gains or losses, and loss of conditioned air to offer input on product performance and environmental conditions while in use.

However, it appears that there has not been much investigation in these areas. Nanotechnology has been used in the development of high-performance steel. Copper nanoparticles from grain boundaries are introduced to low-carbon HPS steel. The microstructure changes that result in tougher, more weldable, and more corrosion-resistant HPS steel. A thinner section of usage may be produced by a high strength paired with a high elasticity modulus. The broadly utilized stainless steels and their twisted variations are anticorrosive in encompassing conditions due to passivation layers composed of chromium oxides. Expectedly, erosion and disintegration of the steels are credited to the breakdown of such layers but seldomly to the beginning that depends on surface heterogeneity at the minuscule level. The nanometer-scaled chemical heterogeneity at the surface revealed by means of spectro-microscopy and chemometric examination out of the blue overwhelms the breakdown and erosion behavior of the cold-rolled Ce-modified 2507 super-duplex stainless steels (SDSS) over its hot-deformed partner [108].

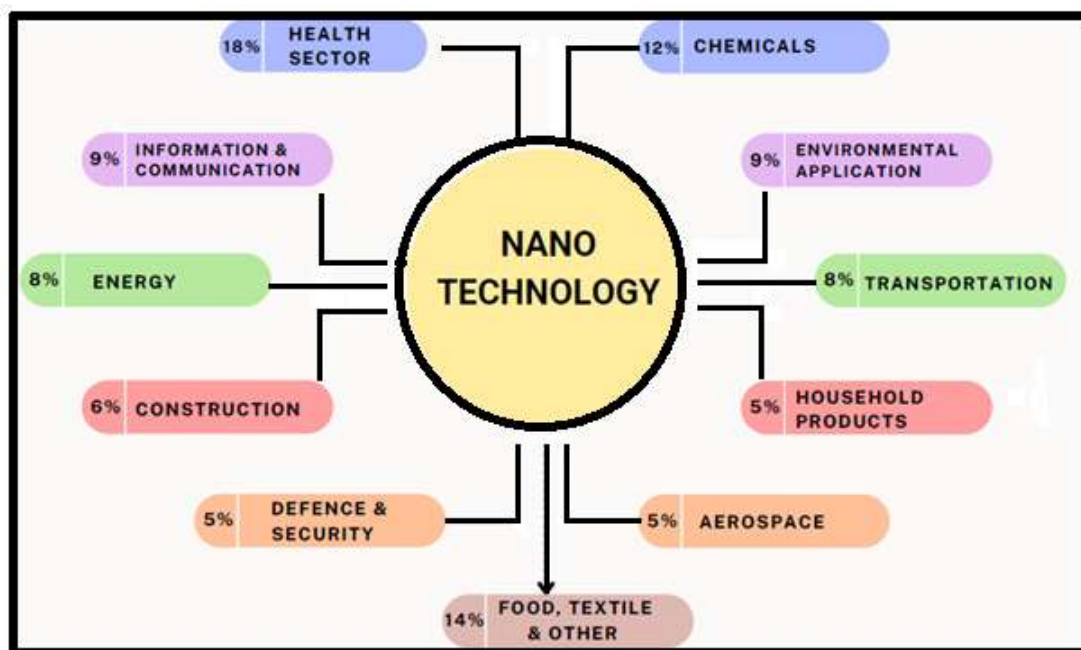
## **IX. CHALLENGES AND FUTURE DIRECTIONS**

For cement and concrete in the building business, nanotechnology has ushered in a new era of possibilities. Structures that are more resilient, long-lasting, and eco-friendly have been made possible by the incorporation of nanomaterials. Nanotechnology in cement, which is still in the research and development stages, has the potential to revolutionise the construction industry by providing sustainable solutions and pushing the limits of what is feasible for contemporary building design and infrastructure. Nanotechnology has great potential, yet it also has drawbacks. Large-scale nanoparticle synthesis and homogeneous nanoparticle dispersion inside the cement matrix are still active research areas. Furthermore, it is important to carefully assess how nanoparticles will affect the environment and human health in the long run. In the future, scientists are investigating novel approaches like smart cement, which has nanosensors and can give real-time structural health monitoring. Additionally, developments in nanotechnology might result in the creation of cement-based materials with improved thermal insulation qualities, which would help to create structures that use less energy.



## X. CONCLUSION

Applications of nanotechnology in building have enormous potential, according to predictions. The cumulative effects of even small material and process improvements could be substantial. Numerous new opportunities are anticipated to emerge in the upcoming years due to the promising potential of nanotechnology to enhance the performance of concrete and to result in the development of novel, sustainable, sophisticated cement-based composites with distinctive mechanical, thermal, and electrical properties. To explain the science behind changes in material characteristics, mechano-chemical processes occurring at the nanoscale in the materials are described. Scientists and engineers are now able to learn more about concrete at scales ranging from the atomic to the continuum thanks to developments in equipment and computational research, as well as the impact of nanoscale features on durability and performance. This knowledge is essential for estimating the service life of concrete and for offering fresh perspectives on how to enhance it. However, before the full potential of nanotechnology can be realised in concrete applications, current challenges need to be overcome. These challenges include proper dispersion, compatibility of the nano materials in cement, processing, manufacturing, safety, and handling issues, scale-up, and cost. The improvement in material performance is projected to have the biggest influence on the economy and the building sector in the near to medium term. In the medium to long term, the development of nanotechnology will produce really new methods for designing and creating materials and buildings with significantly increased energy efficiency, sustainability, and environmental adaptability. Although the field is vast, promising, and developing extremely quickly, there are some issues that need to be addressed by researchers, and solutions should be discovered as soon as possible, if nanotechnology is to be elevated from a high-tech status to one of the greatest blessings to society in general, and to engineers in particular.



**Figure 1:** Applications of Nanotechnology in Different Areas [1].

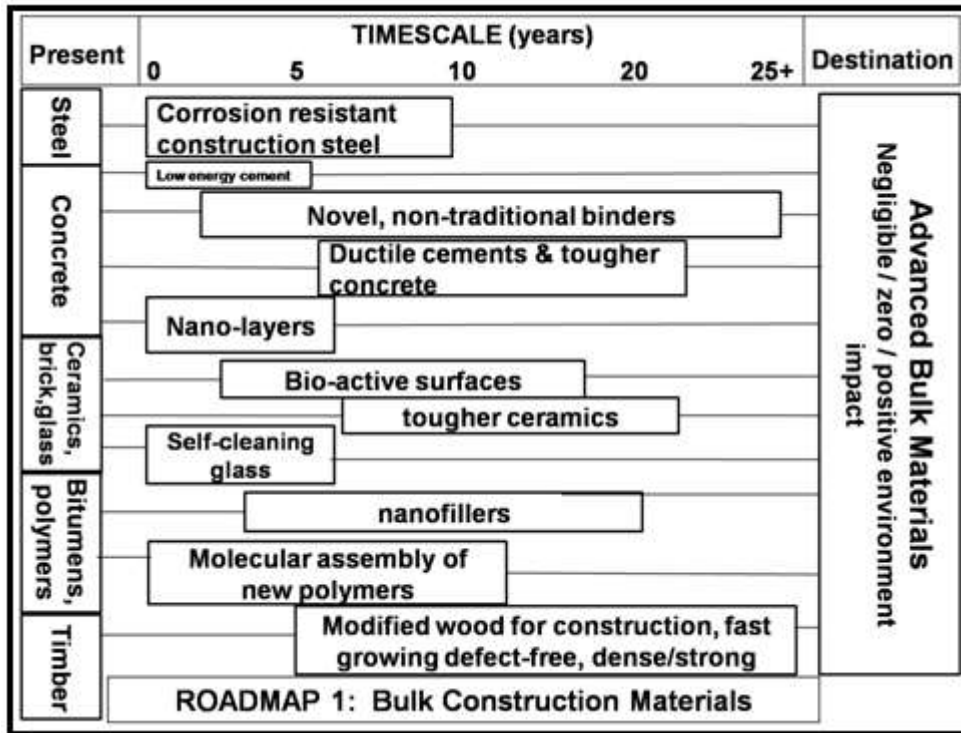


Figure 2 (a): Roadmap 1 for the Potential Use of Nanotechnology in Bulk Construction Materials [1].

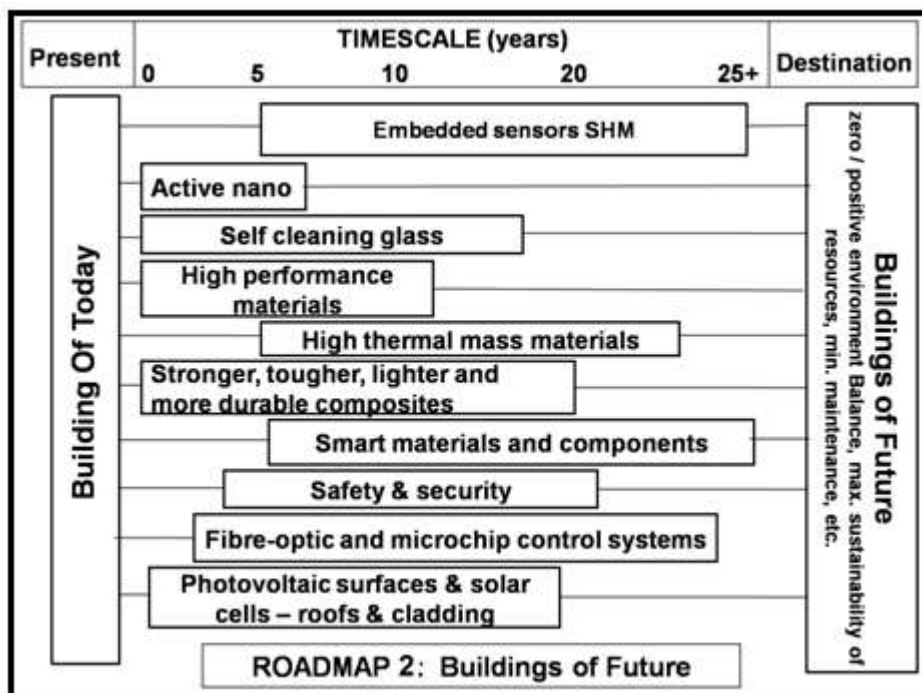
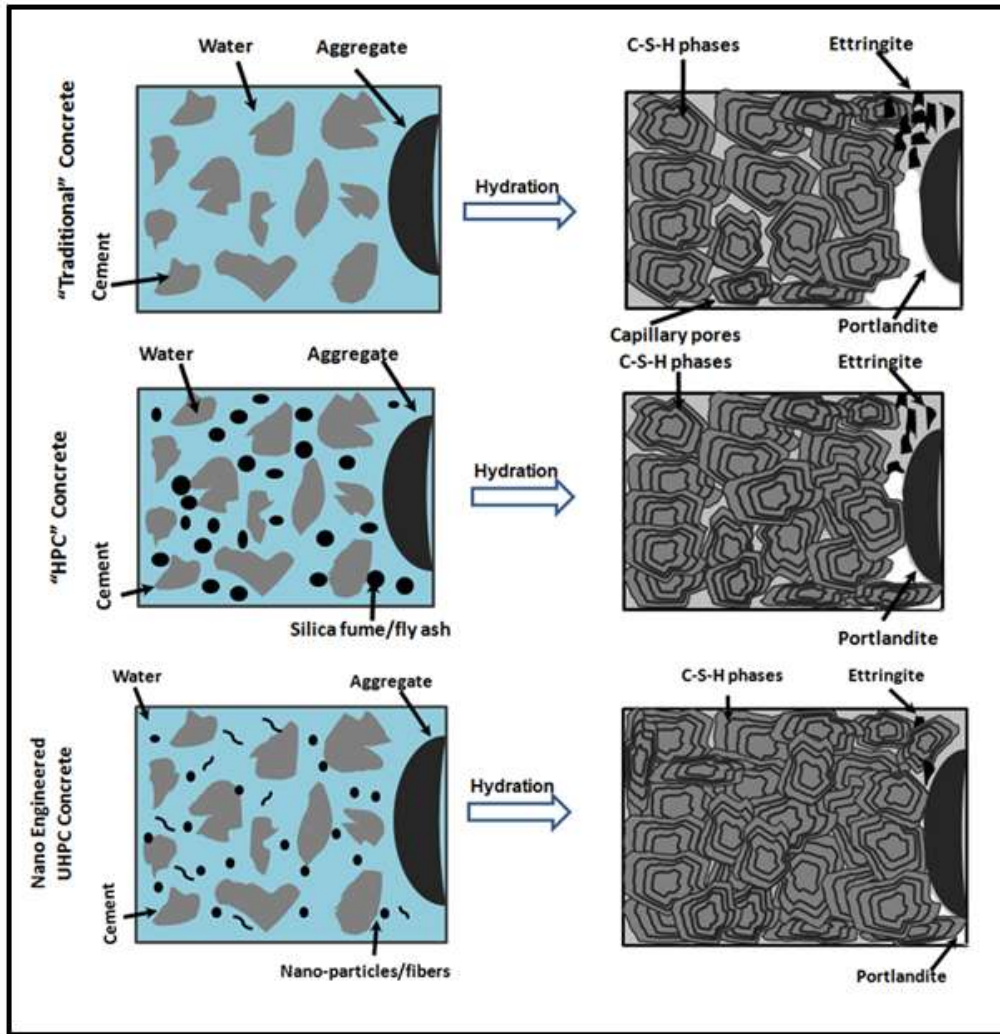
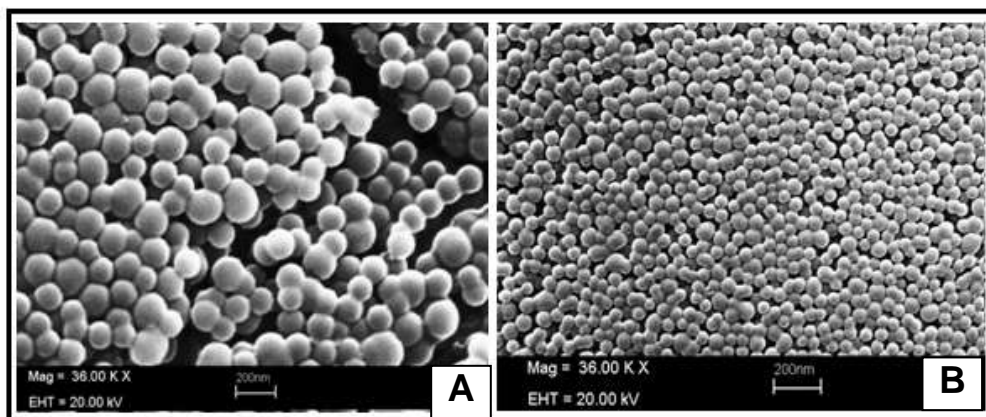


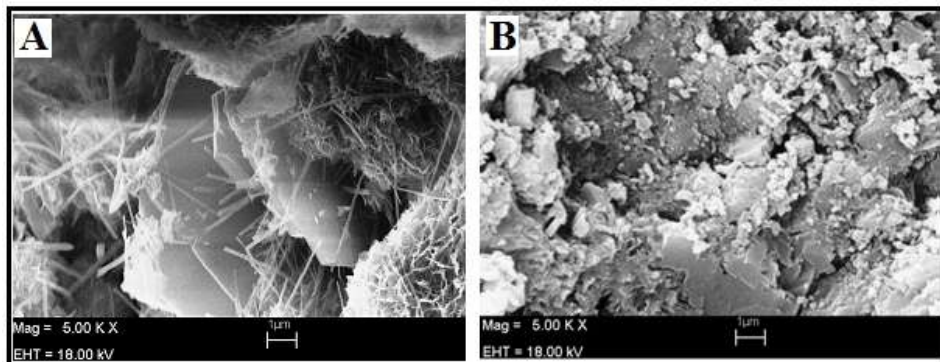
Figure 2 (B): Roadmap 2 for the Potential use of Nanotechnology in Future Buildings [1].



**Figure 3:** Traditional, High Performance and Nano-Engineered UHPC Concrete.



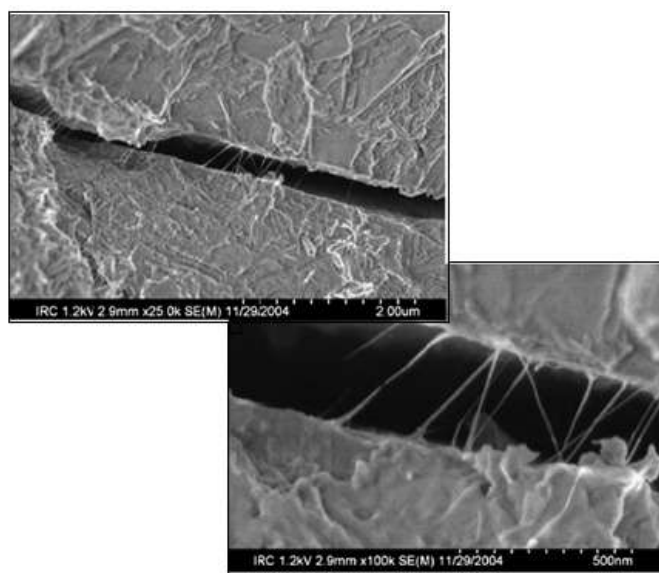
**Figure 4:** SEM Micrographs of Synthesised Silica Nanoparticles (A) Without Surfactant (~150nm), (B) Using Surfactant (~50nm) Respectively [43].



**Figure 5:** SEM Micrographs of Plain Cement Paste (A) And Nano Silica Incorporated Cement Pastes (B), Respectively [44].



**Figure 6:** N-TiO<sub>2</sub> Coated Jubilee Church In Rome [59].



**Figure 7:** Crack Bridging Observed in Cement-CNT Composites [74].

**Table 1: Silica Nanoparticles of Various Morphology and Particles Size Synthesised Using Various Methods.**

Authors	Particle size in nm	Morphology of silica nano particles	Synthesis process	Ref. no.
Yang, <i>et al.</i>	50	Nano-tube	Sol-gel method	[41]
Huet, <i>al.</i>	20-300	Needle-shaped hollow	Sol-gel method	[42]
Kim <i>et al.</i>	400	Cubic type hollow	Sol-precipitation method	[43]
Wang <i>et al.</i>	30	Nano-cubes	Sol-gel method	[44]
Enrichiet, <i>al.</i>	10-300	Monodisperse, Spherical	Modified Stober method	[45]
Zheng <i>et al.</i>	30-110	Ellipsoid, Hollow Sphere	Microemulsion method	[46]
Xu <i>et al.</i>	50-800	Fibber, Spherical	Microemulsion method	[47]
Hanabusaet, <i>al.</i>	20-460	Helical nanostructures	Sol-gel method	[48]

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