Nanomaterials: Properties and Applications in Structural engineering

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Abstract: *Nanotechnology has grown in popularity due to the enormous potential for producing materials and products with diverse properties, allowing significant advancement of existing technology and the development of new innovative technologies. Nanomaterials behave differently at the nanoscale than their conventional counterparts, opening exciting new possibilities in a wide range of construction applications. Nonetheless, the lack of information on nanomaterials' suitability, high costs, and health risks limits their use in construction and structural engineering. As a result, research must be conducted to provide accurate information and facts about the properties and performance of nanomaterials under various load conditions, as well as information on the advantages of using nanomaterials over other construction materials. This paper provides information on nanomaterial properties and how they affect structural materials' microstructure and mechanical properties. It also demonstrates the benefits of using nanotechnology and suggests new possibilities.*
Keywords*: NANOMATERIALS, NANOPARTICLES, PROPERTIES, CONSTRUCTION, COATING*

1. Introduction

The rapid development of nanoscience and nanotechnology in recent years is due to nanomaterials' enormous potential in terms of material and product production. The primary distinction between nanoscience and nanotechnology is that nanoscience provides knowledge of the fundamental properties and arrangements of atoms, whereas nanotechnology uses matter to create new materials with advanced properties [1]. Nanotechnology is the understanding, fabrication, and application of small-scale structures and materials (nanostructures and nanoparticles). It is gaining popularity in almost all engineering branches because it is regarded as an interdisciplinary advanced technology that creates nanomaterials composed of ultra-small particles with properties and behaviors distinct from the larger building blocks of the substances [1],[2]. The independence of electrostatic and quantum forces from gravity at the nanoscale suggests new effects on properties, making nanotechnology more powerful than the traditional practice of manipulating materials on a macro-scale [3]. When obtaining nanoparticles from one matter, surface atoms are much more likely to improve the material's properties than those in the interior [4]. The new properties result from the fact that a small particle has a limited number of molecules and thus interacts differently with the surrounding area [2].

Nanomaterials have at least one nanoscale dimension, and depending on the number of nanoscale dimensions, they can be classified as zero, one, two, or three-dimensional. They are classified based on their morphology (spherical, flat, needle, or random orientations with various shapes such as quantum dots, nanowires, nanotubes, nanofluids, nanobelts, nanosheets, nano-springs, nano-capsules) and composition (monometallic, bimetallic, trimetallic, metal oxide, magnetic, hybrid) [5]. According to their design, nanomaterials can be classified as carbon-based, metal-based, dendrimers, and composites [2]. They can occur naturally as a byproduct of biological systems, accidentally as a byproduct of an industrial process, or deliberately manufactured through some engineering process to obtain materials with specific properties [6].

The use of nanomaterials is appropriate for technological advancement because modifications to the shape, size and internal order of the nanostructures can improve a variety of chemical and physical properties such as melting point, conductivity, absorption, and light dispersion [2]. It's already utilized in numerous engineering disciplines and research areas, but there are still possibilities that are yet to be discovered for further developments. Fig. 1 depicts the interests and role of nanoscience and nanotechnology in science and engineering [1].

Although public awareness of the advantages of using nanotechnology in structural engineering has grown in recent years, there is still a scarcity of information on the subject. This article outlines the most recent achievements in structural engineering of nanotechnology, with an emphasis on properties, the benefits of their application, and their potential for further development and use in construction.

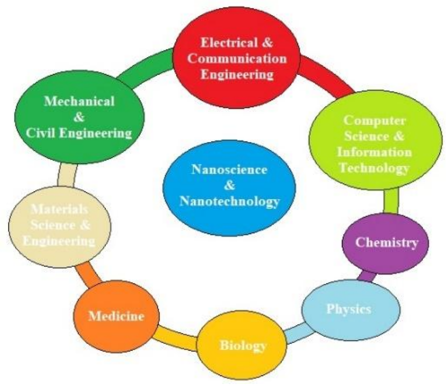

Fig. 1 *Nanotechnology and nanoscience in relation to other sciences and engineering disciplines [1]*

2. Application and properties of nanomaterials in structural engineering

The development of new concepts and understanding of the use of nanoparticles in construction materials is important in structural engineering. Materials can be made stronger, more durable, and tougher using nanotechnology. Furthermore, self-cleaning, insulating, and water resistance properties can be introduced to new structures on their glass surfaces or applied by paint, making these buildings modern and self-sustaining. These materials are used to create stronger and lighter structural composites, low-maintenance coatings, water repellents, UV light protection, and nano-sensors for structural health monitoring [4].

Carbon nanotubes (CNT) are the most commonly used nanomaterials in construction, used for concrete strengthening and monitoring. These nanotubes are made up of graphene-embedded sheets that are rolled into tubes [1]. CNTs are classified into two types: single-wall CNTs and multi-wall CNTs. The single-walled (SW) CNT is made up of one cylindrical shape with various atom arrangements, whereas the multi-walled (MW) CNT is made up of two or more cylindrical shapes packed layer by layer, as shown in Fig.2 [8]. They have significantly higher mechanical properties than steel, such as young's modulus and strength, as well as exceptionally high thermal conductivity along their axis. These carbon-based nanomaterials have good electrical properties and have a growing potential for smart materials and self-monitoring structures [7]. Nanotubes are used in concrete to increase strength and durability, as well as to prevent cracks. They are used in ceramics to improve mechanical and thermal properties, as well as in structures for health assessments [4]. Fullerenes, which have a hollow cage structure of particles with sixty or more carbon atoms and exhibit good electrical conductivity, electron affinity, and high strength [1], are another carbon-based nanomaterial. Carbon nanomaterials may also be used in automobiles as batteries, engine oils, self-lubricating materials, nano-lubricants, and coatings to improve surface wear and antifriction [5]. The molecular structure of carbon can be changed using nanotechnology to a spherical geodesic form, making it more fluid, resulting in the development of nanotubes with an extremely high elastic modulus of 1 TPa, yield strength of 60 GPa, and yield strain of the order of 6% [8]. The CNT can be used to reinforce polymers, glass, composites, and metals in addition to ceramics and cement-based matrix. Materials with a great deal of potential for use in structural engineering include cutting tools, springs, wear-resistant, impact, and earthquake-resistant structures, ductile cement, and glass. In cementitious composites, graphene oxide and graphene nanoparticles are used to enhance the material's mechanical qualities. They are somewhat investigated for application in reinforcing cement composites due to their exceptional elastic characteristics and tensile strength. The structure of graphene and graphene oxide is depicted in Fig.3 [8].

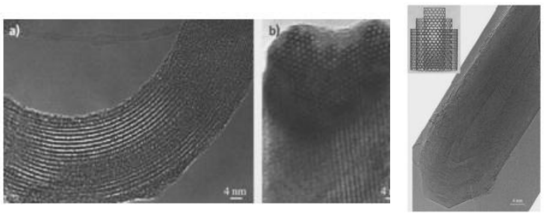

Fig. 2 *Images made of high-resolution transmission electron microscope: a) SWCNT rope – longitudinal view, b) SWCNT rope – cross-sectional view, c) MWCNT with a representation of the layers in the left top corner [8]*

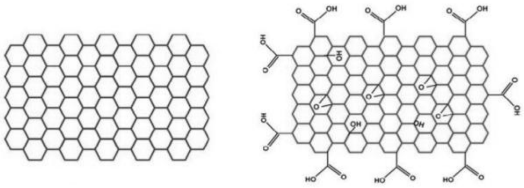

Fig. 3 *Structure of graphene (left) and graphene oxide (right)[8]*

Metal nanoparticles, also known as quantum dots, monometallic oxides (zinc oxide, titanium dioxide, iron oxide), nano-gold, and nano-silver can be used to create nanomaterials [2]. Metal nanoparticles with a high surface area and good absorption of small molecules are formed by reducing divalent and trivalent metal ions with agents [1]. Titanium dioxide (TiO2) is a two nano-sized particle used as a white pigment in paints, cement, windows, and tiles for sterilizing, deodorizing, and anti-fouling properties, and it reduces airborne pollutants through a photocatalytic process. When exposed to UV light, it becomes water-repellent and can be used for anti-fogging or self-cleaning. Furthermore, TiO_2 nanoparticles can be used in concrete as a partial replacement for cement because they increase compressive, flexural, durability, and split tensile strength [10]. Similarly, Fe_2O_3 and CuO nanoparticles are used to improve the mechanical properties of cement and concrete, but they can reduce setting time, workability, and mechanical properties by 3–4%. For denser cement with improved porosity, nanoparticles of silicious dioxide SiO_2 (nano-silica) are used in cement composites. Al_2O_3 nanoparticle use offers comparable advantages when added in small amounts to cement and concrete with an average particle size of 15 nm or less, but it also reduces workability and setting time due to the nanoparticles' quick reactivity with $Ca(OH)_2$ [10]. With the addition of ZrO_2, the concrete's compressive, flexural, and tensile strength can also be increased. However, because of the quick reaction between ZrO_2 and calcium hydroxide, this also affects the workability and setting time, hence superplasticizer is recommended [10]. Nano ZnO_2 particles can help concrete's pore structure and its recovery from polycarboxylate's harmful impacts. The application of CaO_3 nanoparticles provides enhancing characteristics of cement and concrete and increases hydration, setting time, and compressive properties. The silver nanoparticles are used in paints for antibacterial properties on surfaces, this is usually applied to the walls of hospitals to lower the growth of infectious viruses and bacteria [10]. There are also bimetallic nanoparticles (Fe/Pd, Fe/Ag, or Zn/Pd), they can serve as catalysts and reductants [9]. Semiconductor nanomaterials contain metallic and nonmetallic properties. They are used in photocatalysts, electron devices, solar cells, nanoscale electronic devices, light-emitting nanodevices, laser technology, waveguide, chemicals, and biosensors. This type of nanomaterials are made of different compounds and are referred to as II-VI, III-V or IV-VI semiconductor nanocrystals [1]. They have interesting attractive physical and chemical properties, narrow and intensive emission spectra, continuous absorption bands, high chemical and photobleaching stability, processability, and surface functionality [11]. These nanomaterials are advanced materials intended for various applications like new emerging technologies, nanoelectronics, nanophotonic, energy conservation, non-linear optics, miniaturized sensors and imaging devices, solar cells, detectors, and biomedicine [12].

There has been significant progress in exploring a wide range of materials such as nanocomposites and nanohybrids [2]. Nanocomposites are materials with more than one phase where one of the phases has at least one dimension that is less than 100nm, whereas nanohybrids are a combination of 2 or more nanomaterials for satisfying a different function. Compared to the traditional composites, these materials have a high surface volume ratio, and based on their size, shape, or properties they can be different types like ceramic matrix nanocomposites, metal matrix, and polymer matrix nanocomposites [1]. Nano-clay particles are already being added to different products from auto parts to packaging materials as reinforcement in high-performance composites. Nanocomposites with incorporated nanotubes are popular because nanotubes show outstanding properties that in the composite mixture improve the overall properties of the materials. For example, alumino-silicates and nanotubes mixture produces strong and durable films and by further reducing the size of alumino-silicates to 5 to 10 nm more advancement in properties can be achieved [11]. Wrapping existing concrete structures with a fiber sheet matrix of nano-silica show excellent results for strengthening [11].

Steel is extensively used as a construction material in structures that are subjected to cycling loading which can lead to fatigue failure. It is a durable material that holds a high-strength-to-weight ratio in comparison to other construction materials. By adding copper nanoparticles, the surface unevenness can be reduced, and this will limit the stress concentrations and lower fatigue crack initiation [12]. Vanadium and molybdenum nanoparticles can lower fractures in bolts. Stronger steel can be produced by adding nanoparticles in paints and coatings when used as reinforcement bars in concrete [13]. These are known as micro-composite multi-structural formable (MMFX) that are corrosion resistant and have durable properties. The effect of hydrogen embrittlement and their inter-granular cementite phase are reduced through the improvement of steel microstructure [13]. With nanoparticles, steel can become corrosion resistant which is a challenging matter with the traditionally used steel and by adding nanoparticles like calcium and magnesium finer grains in the microstructure of the weld and heat-affected zone can be achieved [14]. Nanotechnology in the metallurgy of steel is used for the reduction of ural steel where microalloying steel with nitride phases is combined with plastic-deformation nanotechnology make the steel stronger [14]. Table 1 contains information on the application of nanoparticles added to traditional materials and summarizes the benefits of their use.

Table 1: *Summarized data on nanomaterials used in traditional construction materials for enhanced properties*

Category	Nanomaterial		Application/Base material	Nanoparticle
Carbon-based nanomaterials	Carbon Nanotube		Cement/Concrete	Improved durability, compressive and flexural strength, self-sensing, and self-cleaning properties,
			Ceramics	Enhancement in thermal and mechanical properties, reduced shrinkage, antibacterial
			Nano electrical mechanical systems	Real-time health assessment of structures
			Solar cell	Effective electron mediation
	Graphene and graphene oxide		Cement/Concrete	improved microstructure, mechanical properties, and durability. improved microstructure, mechanical properties, low cost, accelerated hydration, enhanced corrosion resistance
\Metal- based nanomaterial Metal- based nanomaterial	Semiconductor	Silicon dioxide	Cement and concrete	Enhancement in mechanical strengths and durability, denser cement paste, improved porosity, corrosion reduction, insulating properties
			Glass	Enhancement in mechanical Strengths and durability, nonreflective, fire and heat protection, easy-to-clean properties
			Coatings	Antibacterial, photocatalytic, self-cleaning, hydrophobic, scratch resistance, fire retardant
			Ceramics	Coolant; light transmission; fire resistant
		Titanium dioxide	Solar cell	Producing non-utility power
			Glass	Antifogging, hydrophilicity, fouling resistance, IR reflection, photocatalytic self-cleaning
			Cement and concrete	Self-cleaning, rapid hydration and improvement in mechanical strengths, increased flexibility, pore structure improvement, improved performance at elevated temperatures
			Coatings/Paints	Antibacterial, photocatalytic, self-cleaning, hydrophobic properties, UV protection on wood, active air pollution reduction on asphalt, road pavement blocks, sound barriers, and tunnels
			Solar cell	Non-utility electricity generation
		Ferric oxide	Cement and concrete	Improvement in strength, durability, compression, and abrasion resistance, hydration of cement is increased
		Copper oxide	Cement and concrete	Improved mechanical strengths and durability, reduced the porosity
			Steel	Improved weldability, formability, and corrosion resistance
		Calcium carbonate	Cement and concrete	Improve rheological properties of concrete, increased rate of hydration, setting time, and improve compressive strength
		Chromium Oxide	Cement and concrete	Improves properties of concrete, higher mechanical strength, and durability properties
		Aluminium oxide	Cement and concrete	Compacted microstructure, decreased porosity, enhanced compressive strength, frost resistance, accelerated hydration, reduced water absorption
			Coatings	Scratch resistance
		Zirconium oxide	Cement and concrete	Enhancement in mechanical strengths
		Zinc dioxide	Cement and concrete	Advancement in mechanical strengths, antibacterial properties
			Coatings/Paints	Antimicrobial activity, UV protection
		Silver (Ag)	Paints	Antimicrobial properties, reduce the growth and multiplication of fungi, viruses and bacteria

3. Conclusion

The interest in nanomaterials and their application is constantly growing in many industries. It opens a variety of new possibilities in structural engineering for implementing novel innovative technologies and solutions through improving the properties of the available traditional materials and obtaining and with that obtaining a wider spectrum of new materials. The basic properties of the materials on the nanoscale level bring up significant changes in the mechanical, physical, and thermal properties. The research and applications of nanomaterials are mainly focused on the understanding of the nanostructure of materials and their modification, functional films and coatings, smart structures and devices, and their effect on the environment and health [5]. In structural engineering, there are carbon-based, metal-based nanomaterials, semiconductors, dendrites, nanocomposites, and nanohybrids that can improve the construction materials and bring them completely new capabilities. Table 1 summarizes all of the benefits that nanoparticles bring to materials like cement, concrete, glass, coatings, composites, and steel. It is evident that nano-alumina, nano-titania, nano-silica, nano-magnesium oxide, nano-zinc oxide, silver nanoparticles, carbon nanotubes, or graphene derivatives may have enhanced hydration, microstructure, porosity, and thus mechanical properties and transport-related properties of cementitious composites and introduce new properties such as self-cleaning, self -sensing and antimicrobial properties. There are most recent advancements in applications of nanomaterials in cement composites and structural health monitoring, but the industrial-scale application and toxicity remain a challenge for further development of nanomaterials. Also, lowering the already high energy consumption in buildings and structures is the possible direction of future investigations. A broader perspective should be considered when investigating the possibilities of nanomaterials for enhancing sustainability. Improving the properties of materials, and conserving energy and toxicity are important and should be a high priority for further investigations. Advanced analytical techniques are required for the detection and characterization of nanomaterials realization or incorporation in construction materials [8]. This paper presents a review of the achievements in structural engineering with an emphasis on properties and applications. Further investigation should be done on the sustainability possibilities of incorporating nanotechnology in the construction industry.

References

[1] L. A. Kolahalam, I.V. K. Viswanath, B. S. Diwakar, B. Govindh, V. Reddy, Y.L.N. Murthy, Review on nanomaterials: Synthesis and applications, in: Materials Today: Proceedings, Vol. 18, 6, 2182-2190 (2019)

[2] A. Bratovcic, Different Applications of Nanomaterials and Their Impact on the Environment, SSRG International Journal of Material Science and Engineering, Vol. 5, 1, 1-7, (2019)

[3] A.Srivastava, K. Singh, Nanotechnology in civil engineering and construction: a review on the state of the art and future prospects, Proceedings of Indian Geotechnical Conference, 1(024), 1077-1080, (2011)

[4]F.Trotta, A.Mele, Nanosponges: Synthesis and applications, Chapter 1 Nanomaterials: Classification and properties, 1- 26, (2019)

[5] K. RB Singh, P. R. Solanki, B.D. Malhotra, A. C. Pandey, R. P. Singh, “Introduction to Nanomaterials: An Overview toward Broad-Spectrum Applications”, In: Nanomaterials in Bionanotechnology: Fundamentals and Applications, Chapter: 1, Publisher: CRC Press (2021)

[6] M.N.O. Sadiku, Y.P. Akhare, A. Ajayi-Majebi, S.M.Musa, Nanomaterials: A Primer, IJASRE, Vol. 7, 3, 1-6, (2021)

[7] M. Krystek, and M. Górski, "Nanomaterials in Structural Engineering", in New Uses of Micro and Nanomaterials, London, United Kingdom: IntechOpen, (2018) [Online].

[8] H.V. Tien, G. Ngoc Ha, V. P. Phuong Trang, V. Bao Khanh, Nanomaterials in construction: an overview, Tạp chí Khoa học công nghệ và Thực phẩm **15** (1), 34-45, (2018)

[9] W. Zhu, P.J.M. Bartos and A. Porro, Application of nanotechnology in construction: Summary of a state-of-the-art report, Materials and Structures / Matériaux et Constructions, Vol. **37**, 649-658, (2004)

[10] M. Daniyal, A. Azam and Sabih Akhtar, Application of Nanomaterials in Civil Engineering, Chapter 6, 169-189 (2018)

[11] S. Suresh, Semiconductor Nanomaterials, Methods, and Applications: A Review, Nanoscience and Nanotechnology 3(3), 62-74, (2013)

[12] A. A. Firoozi, M. R. Taha, Ali Asghar Firoozi, Nanotechnology in Civil Engineering, EJGE, Vol. 19 4674 -4682 (2014)

[13] A. Mohajerani, L. Burnett, J. V. Smith, H. Kurmus, J. Milas, A. Arulrajah, S. Horpibulsuk and A. A. Kadir, Nanoparticles in Construction Materials and Other Applications, and Implications of Nanoparticle Use, Materials **12**, 3052 (2019)

[14] A.A.Ali, Nanotechnology in Civil Engineering Construction, International Journal of Structural and Civil Engineering Research, Vol. **9**, No. 1 (2020)