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A Comprehensive Review of Opportunities of Nanomaterials in Stabilization and Construction Industry

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Abstract: Nanomaterials can be defined as materials possessing, at minimum, one external dimension measuring 1-100nm. Nanomaterials can occur naturally, be created as the by-products of combustion reactions, or be produced purposefully through engineering to perform a specialized function. These materials can have different physical and chemical properties to their bulk-form counterparts. Considering these particle sizes, a new approach is proposed to use the nanoparticles in the geotechnical engineering to understand the nature of soil as nanoparticles will interact with soil particles more efficiently due to the advantage of their size i.e. 1nm to 100nm. As the new construction sites has been significantly increased in the area of poor-quality ground several new approaches of stabilizing the soil underneath are introduced and one of these techniques are using the nanoparticles to improve the index properties of soil as well as strength of soil so that desired stability can be achieved. Different types of nanomaterials which can be used for the purpose of stabilization of soil are SiO¬2, TiO2, Al2O3. This paper also addresses the use of nanomaterials in housing construction, comparing their influence at the technical-structural level. Materials such as titanium dioxide, carbon nanotubes, nano silica, nanocellulose, nano alumina, and nano clays were analyzed. It was obtained that these nanomaterials can improve the structural, thermal, and functional properties of construction materials. In addition, they are related to increased durability, increased mechanical strength (>20 %), reduced thermal conductivity, and self-cleaning capability. Therefore, the use of nanomaterials promises to improve the sustainability and efficiency of housing construction.

Index Terms: Nanomaterials, carbon nanotubes, nano silica, nanocellulose, nano alumina, nano clays

I. INTRODUCTION

Nanotechnology is the science and engineering of functional systems at the molecular scale. In its original sense, nanotechnology refers to the projected ability to construct items from the bottom up making complete, high-performance products. Considering the particle sizes, a new approach is proposed to use the nanoparticles in the geotechnical engineering to understand the nature of soil as nanoparticles will interact with soil particles more efficiently due to the advantage of their size i.e. 1nm to 100nm. The outstanding effects of nanotechnology has not been implemented in the field of geotechnical engineering as it might be due to the fact that the field of nanotechnology can be intermixed with other fields and require quite a lot of knowledge to understand the concepts of this exciting field. Due to insufficient nanoscale research in geotechnical engineering many facts are left behind, as most of the soil and rock minerals are Nano-particles and their chemical reaction occur at nanoscale. So, it can be easily said that nanotechnology has a great potential to use in the process of grouting, soil stabilization etc. From the past researches, it was seen that additives can be used to improve the strength of the soil which in turn increase the stabilization of weak soil, so it was assumed that Nanoparticles can be utilized in the field of Soil and foundation engineering. The implementation of nanotechnology and specifically the use of nanomaterials with advanced functional properties can positively impact the sustainable development of the housing construction industry, since these nanomaterials provide technical, economic, environmental, and aesthetic advantages, contributing to the achievement of Sustainable Development Goals. Different nanoscale materials are being used as additives in house construction, highlighting their applications as thermal insulators, air purifiers, self-cleaning surfaces, anti-corrosives, moisture and pathogenic microorganism repellents. In addition, some nanoparticles can be used as cement binders, which involves higher yields and consequently lower costs in the construction sector. Both from environmental, economic, and quality perspectives, nanomaterials bring functional properties to traditional housing construction methods. For example, the addition of nanosilica (SiO_2) and nanoalumina (Al_2O_3) can increase the durability and strength capacity of cement-based structures by up to 20%. Carbon nanotubes (CNTs) optimize strength with high moduli of elasticity and improve thermal and electrical conductivity.

Meanwhile, semiconducting nanomaterials such as titanium dioxide (TiO2) and other photocatalysts that can be incorporated at the concrete preparation stage can self-clean the environment and catalyze the photodegradation of gases such as NOX, COX, and other pollutants generated inside a house. Nanoclay has also been employed to improve the mechanical performance of concrete by decreasing permeability and shrinkage, which translates into less chance of crack formation and damage to architectural structures. Although there is a high number of works that have reviewed the use of nanomaterials in the construction industry, there is a gap in the application of these nanomaterials in residential construction. In addition, there is a scarce approach to the preparation strategies of nanomaterial-enhanced construction additives and nanoparticles obtained from eco-friendly sources, as well as their enhancement effect on the resulting material. Therefore, this manuscript aims to review recent advances in the use of nanomaterials in residential construction and soil stabilization, analyze preparation methodologies, and how these mixtures can enrich the characteristics of concrete, lightweight materials, and surface coatings to promote the construction of more efficient and environmentally friendly infrastructures.

II. NANOTECHNOLOGY IN GEOTECHNICAL ENGINEERING

The section explained the stabilizations of weak soil with nanomaterials applied to rectify many constructions, geotechnical, slope stability, and transportations failures. Table 1 consists of the stabilization of different types of soils with different materials with varying percentages. Table 1 explained that in which percentages strengths deviations happened, that percentages recorded as optimal dosages based on the UCS, plasticity index, specific gravities, and compaction characteristics. The index and engineering properties of weak soil improved all strengths with optimal dosages of nanomaterials. The nanomaterials added to weak soil will complete in soil manipulation at the atomic level and influence improving all the properties of the soil. The nanomaterials treatment is very cheaper with using very low percentages.

Table 1 Soil stabilization with different materials

Soils, admixtures	Percentages (By weight)	Optimal percentage	Conclusions	References
Sandy soil nano silica, and cement	0, 4, 8, and 12% 8%	8%	UCS, compaction characteristics improved with optimal dosages of nanosilica to sandy soil, microanalysis by SEM and AFM. CSH gel formed than CH gel	[39]
Soils, nano silica	0.5–4%	1%	UCS improved and analyzed SEM, FT-IR	[17]
Silty soil, nano silica	1–12%	8%	Cohesion improved 117%, angle of inter friction improved 128.27% under normal stress 100 kpa	[10]
Iron slag, nanosilica	1–20, 0.1%	10%	Freeze–thaw durability improved on the addition of NS and slag	[4]
Residual soil, nanosilica	0.2–1%	0.4%	Strength, CEC, and ER improved CSH gel formed	[37]
Collapsible soils, nanosilica	2–5%	5%	Engineering properties improved	[30]
Weak soil, nano Ca	0.4–1.2%	1.2%	UCS, residual strength improved	[31]
BC soil, terrasil	0.03–0.09%	0.07%	UCS, permeability characteristics improved	[36]
Soil, terrasil	0.8- 1.2%	1%	Index and engineering properties improved with optimal dosage	[4]
Clay soil, terrasil	0.01–0.08%	0.041%	CBR strength improved from 6 to 13%	[15]
Soft clay, terrasil	l 0.05–1%	0.07%	6 times improved the characteristics of CBR as subgrade	[40]
Soft clay, fly ash	5–10%	7%	Settlements controlled	[27]

III. EFFECT OF NANOPARTICLES ON COARSE GRAINED SOIL AND FINE GRAINED SOIL

A. Colloidal Silica

It was stated that when 32 wt.% colloidal silica was used in the coarse-grained soil then unconfined compressive strength of 335 KPa was achieved [40]. It was indicated that when sand was grouted with silica then compressive strength was increased and when silica was increased up to 27% then after 7 days of curing compressive strength reached the value of 400KPa [27]. Tri-axial test was also conducted on the sand and it was noted that sand was more capable of resisting the force inform of structural weight when Nano-material was used as it was found out that when 4.5 wt.% colloidal silica was introduced in the specimen having 45% relative density, the liquefaction resistance was same as that of the untreated specimen which have the relative density of 75% or more [35]. It was also found that colloidal silica was used as grouting material and with the help of centrifuge modelling the loose sand with lesser strength was stabilized [5]. Colloidal silica was also injected into the wells as an additive so that settling of loose soil can be reduced by explosion and it was seen that settling was reduced by 40% [5].

B. Nano-clay

When Nano-clay was used in the soil, plastic and liquid limit was calculated and it was found out that when 0.5 wt.% of Nano clay was used then significant improvement was not seen but when 1 wt.% of Nano clay was added than increment of 13% and 38% was seen in liquid limit and plastic limit respectively which in turn justifies that plasticity index was decreased by 40% [23]. Nano-clay was used to improve the Strength properties of sand which was done by using cement and California bearing test (CBR) and unconfined compressive strength (UCS) was done. Nano clay was used with 0.5, 1, 2, 3 and 5 wt.% and cement were used with 7 wt.% of the dry weight of soil, it was seen that after 7 days of curing age CBR value was increased by approximately 25% as the former value of CBR was 84.66 and was increased to 112.75 [2]. It was seen that when 2% to 4% Nano-clay was added then compressive strength of soft soil was increased from 3% to 22% [18]. Researchers stated that the change in water-binder ratio effects the compressive strength of MPC paste as [19] stated that with the increase of w/b ratio the compressive strength decreased suddenly and at 3, 7 and 28 days of curing the strength loss was 39.7%, 39.4% and 40% respectively. [24] stated that when w/b ratio was increased from 0.22 to 0.30, compressive strength was decreased from 45 MPa to 38 MPa after 1 day of curing age because of extra water present in matrix the structure became permeable and resulting in decrease in strength.

C. Nano Alumina

It was investigated that when nanoscale aluminum oxide was used in the cohesive soil which contained the sewage sludge cement with the ratio of cement and ash of sludge from sewage of 1:3 and it was found out that unconfined compressive strength of the specimen treated with 1% nanoscale aluminum oxide was 4.2 times higher than that of untreated specimen. It was also found out that when specimen was treated with 0% and 1% nanoscale Al_2O_3 the value of CBR was found out to be 60.2 and 70.1 respectively [18]. The value of plastic index of specimen treated with Al_2O_3 was found out to be less than the untreated specimen [18].

D. Nano Clay

It was stated that when Nano clay was used in the silt stabilization (classified as MH and ML) and unconfined compressive strength test (UCS) and California bearing ratio test (CBR) was performed to identify the strength. Nano clay was used in 0.5, 1, 1.5 and 2 wt.% and it was found out that CBR value of untreated specimen was 5 and 8 for MH and ML and when Nano clay was added with 1.5 and 1 wt.% the CBR value was increased by 68.75% and 77.7% for MH and ML [19]. It was found out that when 0.1, 0.2 and 0.3 wt.% Nano clay was used the geotechnical properties of soft soil changes as plastic limit and liquid limit of soft soil decreased and plasticity index of soil also decreased whereas maximum dry density of soil was increased when Nano clay was used as additive [24].

IV. NANOTECHNOLOGY IN THE CONSTRUCTION INDUSTRY

Nanotechnology has experienced exponential growth in recent decades, revolutionizing sectors as diverse as medicine, electronics, and construction. This is based on the development of materials with unique physical and chemical properties, which offer enormous potential to transform the housing construction industry. The latest advances enable the creation of stronger, more durable, efficient, and sustainable structures, directly addressing the challenges of climate change and global urbanization. The emergence of nanomaterials in the field of construction dates to the mid-1980s, with the development of carbon-based structures. However, their effective integration in construction processes gained importance after the discovery of fullerenes in 1985 and CNTs in 1991, which established a solid foundation for their application on larger scales.

Starting in the 2000s, the practical implementation of these materials began to take shape thanks to continuous advances in research, innovation, and development. Today, nanotechnology research has advanced considerably, driving the creation of increasingly advanced, selective, and efficient nanomaterials. The introduction of innovative materials such as titanium dioxide, silica, and nano clays has expanded their capabilities in the construction sector, enabling the use of these advanced nanomaterials to reorient trends in sustainable construction projects. This manuscript focuses on five specific nanomaterials: titanium dioxide, carbon nanotubes, nano silica, nano alumina and nano clay. These nanomaterials are selected due to their demonstrated ability to improve the structural, thermal, and functional properties of materials used specifically in residential construction. Titanium dioxide is renowned for its photocatalytic properties and self-cleaning capabilities. Carbon nanotubes are included for their exceptional mechanical strength and conductivity. Nano silica has been chosen for its ability to improve the durability and mechanical performance of concrete. Nanocellulose is an admixture that offers renewable and biodegradable options, while nano alumina provides significant improvements in compressive and tensile strength. Finally, nano clay is known for its potential to improve the thermal stability and mechanical properties of cement-based materials. The selection of these nanomaterials was guided by an extensive review of the available literature, focusing on those that have shown promise in laboratory and field studies as additives in residential construction. Although other nanomaterials also have potential, they were omitted from this study due to insufficient empirical data or limited application in residential construction contexts.

V. TYPES OF NANOMATERIALS USED IN THE CONSTRUCTION INDUSTRY

A. Titanium Dioxide

TiO2 is a nanomaterial (10–100 nm) noted for its photocatalytic ability, an attribute exploited to increase the durability, strength, and efficiency of composite materials in the construction industry. Integrating TiO2 into photocatalytic cementitious composites represents an innovative approach to extend the service life of buildings and mitigate environmental pollution. This nanomaterial is appreciated for its economic accessibility, chemical stability, and non-toxic character, facilitating the reduction of urban pollutants such as nitrogen and carbon oxides when combined with cement. The application of TiO2-based coatings on construction materials has proven to be effective in increasing their lifetime. In terms of nanomaterial innovation, a process has been developed to synthesize single crystalline TiO2 nanowire arrays by an alkaline hydrothermal method, which includes ion exchange steps and topotactic transformation by calcination. This procedure results in nanowires that improve the efficiency of photocatalytic and photovoltaic devices. The ability of TiO2 to be integrated into composites is due to its chemical and physical compatibility with a wide range of materials, which allows its adaptation to different morphologies and particle sizes. This adaptability ensures a uniform dispersion of TiO2 within the composite, optimizing the interaction between this nanomaterial and the host material. Such uniformity is essential not only to enhance the photocatalytic properties of TiO2 but also to reinforce the mechanical strength and durability of the composite material.

B. Carbon Nanotube

CNTs are symmetrical structures made up of carbon atoms with a diameter of 3–15 nm, which are geometrically arranged as hexagons and pentagons. These nanoparticles are widely used due to their structural, electrical, and mechanical characteristics, so their low cost, high conductivity, and high surface area position them as an interesting reinforcement of polymeric materials, metal alloys, and ceramics. These nanomaterials can be found as graphene sheets, including single-walled and multi-walled CNTs. Moreover, CNTs are presented as one of the most representative active electrode materials, due to their chemical and mechanical stability. Incorporating carbon nanotubes into building materials enhances their mechanical characteristics while also contributing to improved electrical conductivity and thermal stability. To the fullest extent possible, these nanomaterials must be able to create robust contacts with the host material and diffuse uniformly throughout a matrix . As a result, CNTs offer a cutting-edge approach to the synthesis of multifunctional materials that is consistent with modern developments in materials engineering as well as the construction of high-performing, sustainable technologies.

C. Nanosilica

Nanosilica is a compound of tetrahedral geometry defined by siloxane bridges (O-Si-O) that form a unique nanometric structure, with advanced applications in scientific and industrial fields. The properties of nanosilica, such as morphology, particle size, pore size, and shape, crystallinity, biocompatibility, photoluminescence, and thermoresistance, depend on the synthesis methodology employed, which gives it potential advantages for its versatility and applicability.

Nanosilica also exhibits very stable thermal and electrical characteristics, showing low levels of electrical conductance due to its high band gap and acting as a thermal insulator due to its low conductivity. These properties enhance the application of silica nanoparticles as an adjuvant in cement mixtures. In addition to its contribution to the durability and strength of structures, nanosilica can optimally maintain thermal conditions inside buildings (thermal insulators), which is an important advantage in areas that are exposed to high temperatures. This ability to improve both the mechanical and thermal properties of composite materials underlines the importance of nanosilica in the development of innovative and sustainable solutions in construction and other industries.

D. Nanoalumina

Nanoalumina or alumina nanoparticles, is a form of aluminum oxide that exhibits exceptional properties due to its nanometer scale (1–100 nm). The synthesis of these nanoparticles is carried out through diversified methods designed to obtain specific structural characteristics. It is also an important electrical insulator with high dielectric strength and can be favourably used as a coating for construction materials, as it protects surfaces against wear and corrosion. A common synthesis method for mesoporous alumina involves a solgel process, employing aluminum isopropoxide and a nonionic block copolymer P123 as a structural mold in an acidic aqueous environment. By modifying parameters such as the amount of P123, HNO3, Al (NO3)3 doping ratio, and calcination temperature, it is possible to precisely control the surface area, pore volume, and pore size of the resulting alumina. These structural properties are crucial for their application in adsorption processes. Additionally, the creation of nanoalumina can also involve the use of natural resources, such as Neem leaves, for the biosynthesis of alumina nanoparticles. This biosynthesized powder has been shown to improve the mechanical and thermal properties of hybrid fiber composites including sisal, coconut, and banana fibers. Another approach involves the use of high-pressure radiofrequency plasma reactors to transform micrometer-sized alumina fragments into spherical nanoalumina. Regarding the incorporation of nanoalumina in composite materials, its addition to glass fiber and polypropylene-reinforced composites has significantly improved their mechanical and thermal properties, making them suitable for orthopedic devices.

E. Nanoclay

Nanoclays is a material composed mainly of silicate minerals that occur in both natural and synthetic forms. They have captured scientific and technological interest due to their distinctive properties and potential for application in a variety of fields. Synthesis of nanoclays can involve several methods, including chemical modification and exfoliation processes. For example, functionalization of sodium montmorillonite with aminosilane followed by grafting with amino acid monomers is a novel approach to produce nanoclays with increased interlayer spacing and thermal stability, which are essential for fabricating clay-polymer nanocomposites. In addition, organ modified nanoclays can be synthesized by inserting quaternary ammonium methacrylates into the interlayer space of the nanoclay via a cation exchange reaction, which may be suitable for applications in industrial materials . Also, the incorporation of nanoclays into various polymers allows the creation of nanocomposites with improved properties, which have found application in sectors such as aerospace, automotive, construction, petroleum, biomedical, and wastewater treatment. In the field of food and beverage packaging, nanoclays are explored for their potential as antimicrobial agents and as part of colorimetric indicator systems. In the field of construction, nanoclays are being studied for their biocompatible properties with cement-based products, unique shape, high surface-to-volume ratio, and loading potential. Research in polymer-nanoclay composites is an emerging area that seeks to develop new materials with superior properties, taking advantage of the unique characteristics of nanoclays to innovate and improve existing applications in residential construction.

VI. CONCLUSION

In this paper we found out the advancement in geotechnical engineering by using the nanotechnology to strengthen and providing adequate strength to the soil so that construction can be done on these types of soil. Nanoparticles are novel material and has extremely small size which make the specific surface area extremely high so it leads to very high reactivity of Nano particles in the soil matrix.

It was found out that with the addition of Nano particles in the soil the compressive strength of soil was increased substantially and liquefaction of soil was decreased up to some extent and the settlement of soil was also decreased as the resistance of soil towards compression was increased. It should be taken into account that Nano materials act according to their conditions and Table 1 provide the adequate information about the researcher results when they used the Nano particles to stabilize the soil.

The use of nanomaterials as construction additives can lead to a more efficient, cost-effective, and eco-friendly housing construction industry since they can improve the strength of cementitious materials and other construction additives, provide substantial advantages in the resulting mixture, because they act as thermal insulators, increase strength and durability, decrease permeability and provide self-cleaning and purifying properties on surfaces. In addition, they contribute to the safety of engineered structures and thus minimize the consumption of traditional building materials.

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