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REVIEW

Application of Nanotechnology in Soil Stabilization

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ABSTRACT

Nano-technology is expanding its horizon in various science and technology fields. In civil engineering, soil is a complex material and used for various functions and applications. Meanwhile, sometimes an effective soil stabilization technique is needed to fulfil the site criteria and can be achieved by adopting various methods e.g., physical, chemical, thermal or reinforcement using geotextiles and fabrics. The mechanism of soil stabilization using nanomaterials is still unexplored and open to prospective researchers. The present article attempts to touch and explore the possibilities of nano-technology in soil improvement and its applications in various civil engineering works. Microstructural analysis of the nanomaterials treated soils using the latest equipment has also been discussed. The study interprets that the use of nano materials is still limited, due to their high cost and sophisticated handling procedures. Though the use of nanoparticles in soil stabilization results in extraordinary improvements in various soil properties, the improved soil properties could be utilized for various geotechnical projects. The present study bridges the past findings to the present scenario of nanomaterials in soil improvement.

Keywords: Nano particles; Fine soils; Geotechnical engineering; Microstructural analysis; Field application

1. Introduction

Natural soil is very complex and essential for all living organisms on the Earth. Every species of the plants including shrubs, cactus, mushrooms etc. has their unique functions in maintaining the ecosystem [1,2]. Naturally, the plants stabilized the soil beneath the civil structures but unfortunately, humans have not appreciated and cited the fact to date [3–5]. Plants also help to check natural disasters like floods and liquefaction conditions surrounding the erected structures. The fact is that the roots of the plants

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serve as fibers in the soil matrix. A lot of studies conclude that foresting is necessary to prevent air as well as noise pollution [3,6].

Soil stabilization generally modifies and upgrades the soil properties required at the site. This can be done by various methods or sometimes a combination of methods is required [7,8]. The admixtures used and mixed in the soils alter the inherent soil properties and improve the engineering behavior of the soils. Likewise, sand mixing is done to reduce the liquefaction action in the soils [9,10]. Basically, the addition of external materials to the soils is done through two methods; in the first case, natural soils mixed with other stabilizing materials get improved mechanically after changing their gradation and in the later case, the materials react and fill the voids after penetration like jet grouting [11].

Modern nanotechnology is ruling in various fields including engineering. Nanomaterials, by definition, are nanometre sized particles and are considered as a whole unit. In soil mechanics, the clay size varies from 1-2 μm and is a nanoparticle itself. The application of nanomaterials in geotechnical engineering could ingress the new large size particles of concern [12]. But, still some issues as listed follow can hurdle the game changing nano materials: a. Dearth knowledge of basic physics and chemistry to understand the behavior of nanoparticles; b. Unskilled labour; c. Dearer price of the nano materials.

Although there are certain obstacles that deter the widespread adoption of nanomaterials for soil enhancement, researchers have undertaken significant investigations into the use of nanomaterials in soil stabilization. This article provides an overview of the topic, covering the classification, properties, methodologies, advantages, and disadvantages of nanomaterials in the context of soil improvement. Additionally, the article offers suggestions for future directions in this field.

2. Classifications of nanomaterials

A nanoparticle is incredibly small, measuring in the range of 1 to 100 nanometers in size. There is a significant difference between the mechanism applied for soil stabilization to conventional strengthening materials. This difference could be pronounced by the fact that these materials have a larger area to volume ratio irrespective of the shape of the particle and their quantum effects derived from spatial confinement [13]. Nanomaterials can be classified as zero dimensional (0D) or also known as quasi-zero dimensional i.e., having aspect ratio from 1-∞; one dimensional (1D) those have one dimension outside the nanoscale, two dimensional (2D) in which two dimensions are not of nanoscale, three dimensional (3D) also known as bulk nanomaterials and all the dimensions of this kind of nanostructures lie above 100 nm [14]. **Table 1** contains the typical examples of all category nanomaterials.

Table 1. Typical examples of classified nanomaterials.

Type of nanostructure	Examples
0D	Nanograins, Nanoshells, Nanocapsules, Nanorings, Fullerenes, Colloidal Particles, Nanoporous silicon, Quasi-crystals
1D	Nanorods, Nanofilaments, Nanotubes, Quantum wires, Nanowires, Imogolite, Halloysite, Palygorskite, Sepiolite
2D	Discs, Paltelets, Ultrathin films, Superlattices, Quantum wells, Kaolinite, Illite, Smectite, Chlorite, Vermiculite
3D	Bundled nanowires and nanotubes

Though each type of nanomaterial serves specific purposes, 1D nanostructured materials are particularly crucial for applications related to energy, sensing, and biomedical fields. Therefore, it is prudent to explore 1D nanomaterials extensively to gain deeper insights into research involving nanomaterials.

3. Properties of nanostructures

It is a fact that the nanomaterials are of microscopic size therefore, their various physical, chemical and structural properties could serve many functions at the point of their applications. The magnetic, electrical and optical properties of the nanomaterials have wide applications in different fields.

3.1 Structural properties

Structural properties of a material are those properties that express information about the role of the elements in the overall structure of the system. Nanoparticles have a regular crystalline structure and follow a kind of magical number [15]. Scientists believe that the unusual behavior of the nanomaterials is due to their exceptionally high surface area to volume ratio [16,17]. Structural properties of the nanoparticles can only be observed by sophisticated laboratory instruments e.g., X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Small-Angle X-ray Scattering (SAXS), Transmission Electron Microscopy (TEM), Scanning Probe Microscopy (SPM) and Gas Adsorption. The size of the particles can get altered under different laboratory conditions e.g., time, mixing method and additive type etc. [18–20].

In the case of soil stabilization, gelling (gel formation due to chemical reactions) due to nanosilica totally depends upon the mean particle size of nanosilica. As a general guideline, the smaller the particle size will be, the faster the gelling and bonding will be [21]. Nanoparticles produce the bond between soil and admixture, which has some cohesion until the bond gets torn apart along the shear plane [22].

3.2 Physical and chemical properties

In general, the physical properties of material comprise of color, texture, appearance, melting point, fire point etc. whereas common chemical properties are media concentration, reaction with fluids etc. In exceptional, some interesting properties of different nanomaterials can be scribed as gold nanoparticles show the different absorbing capacity to red color with respect to its size i.e., the larger size (90 nm) absorbs the red and the smaller size (30 nm) reflects the red color. Nanostructured TiO_2 has self-cleansing properties but it loses this when used in bulk. Nano gypsum is much harder (3x) than other conventional micro-sized particles [23-27]. Unique chemical properties of the nanomaterials could be used for storing energy from bulk to nano materials, increasing germination in the plants etc. [28,29].

3.3 Mixing methods

Agglomeration during mixing is a common problem associated with the nanomaterials. Hence, when employing nanomaterials for soil stabilization, it is advisable to utilize mixing techniques that reduce agglomeration to ensure effective results. Homogeneous mixing is the key factor in getting the expected results. Researchers have adopted various mixing methods to get a uniform soil-additive mix and added dispersing agents drop by drop to evade the agglomeration effects during mixing. Another important precaution to consider is periodically agitating the mixture to maintain its effectiveness during the soil stabilization process. Additionally, the fusion of two nanomaterials is necessary while dealing with two or more nano sized additives simultaneously [30]. Most of the researchers recommend a water sprinkling on the mix right after mixing the nanomaterials into the soil. A thorough mixing and agitation of the mix is also recommended to get a homogeneous mix [31–36].

3.4 Interaction mechanism

Though understanding the fundamental mechanisms and microstructural behavior of the stabilized soil is not that easy but latest techniques and insights gained through various research made some rational and valid theories to explain the same [37,38]. In the 70's, Lambe and Whitman summarized that the behavior of soil at the macro level is controlled by the interaction at the micro level. During this, the mineralogical and chemical compositions of the stabilized soils are dependent upon the structural rearrangement and environment in which the reactions take place [39,40]. The theories developed in the past say that the cohesion in the soil is the result of attraction forces developed in the soil particles. The swelling characteristics of the soil can be judged after observing the presence of a smectite group in the soil, which is highly vulnerable to swelling and shrinkage. Haematite and geothite (iron oxides) vary in sizes from 10-100 nm and soil containing these oxides can produce a hardened product [41]. High thermal conductivity, an indirect method for predicting dry density and gradation, is more in sands containing silica with respect to the sands containing mica. High clay content imparts the swelling characteristics to the soils, which is also a function of high plasticity. Surface forces in clays are higher than sands and silts. On a thumb rule, high clay content in the soils is responsible for high plasticity and high swell-shrinkage properties in fine-grained soils. Hence, having a profound understanding of soil composition at the micro level can significantly simplify the comprehension of anticipated soil behavior [40,41].

3.5 Microstructural imaging

Microstructural characterization of the specimens is a very efficient and effective tool to analyze the changes that occurred after the soil stabilization using nanomaterials. The microstructural patterns and images are used to study the bonding, cracks, chemical and physical changes in the soils. Though there are numerous microstructural analysis techniques e.g., SEM, XRD, TEM, Field Emission Scanning Electron Microscopy (FESEM), Fourier Transform Infrared Spectroscopy (FTIR), Thermogravimetric Analysis (TGA) and X-ray Fluorescence Spectroscopy (XRF) and so on, but a prior knowledge on these techniques is highly recommended. Micro images are the easiest way to interpret the structural and mineralogical changes in the soils [42]. Among all techniques, SEM is believed to be excellent and can be coupled with the EDX or XRD/XRF. TEM has a different sampling procedure but is an authentic microscopy technique. This technique not only measures the size and shape of the particle but also supplies other relevant information. Atomic Force Microscopy (AFM) has a unique feature that can be used in the presence of air, water and vacuum. XRD is also a simple and cheap technique to know the mineralogy of the nanomaterials [42,43]. On the basis of previous studies, it can also be interpreted that there is no validation method other than microstructural analysis to check the dispersion of nanomaterials and penetration of cementitious gel (gelling) in the soil [43].

4. Soil-nanomaterial interactions

The scarcity of usable land has levied a challenge to the geotechnical engineers to repair the weak soil deposits so that construction can be executed at those sites too. So, the engineers are making efforts to improve the engineering performance of the soils by adding wastes, fibers and nanoparticles. The following subsections summarize the changes that occurred in various soil properties after adding the nanoparticles into different soils.

4.1 Plastic properties

In comparison to alumina, copper nanoparticles were found more effective in decreasing the plasticity index of the soil [44]. Nanoclay has contradictory effects on the plasticity index of fine soils. Some researchers claim that nanoclay decreased the plasticity index up to a satisfactory level while others are in favor of an increase in plasticity index. The quantity of nanoclay to be added to the soil varies from 1%-8%, according to the nature of the soil [45–49]. The reason behind this could be the expansive nature of nanoclay [45]. Whereas, the addition of clayey nano soil, alumina, copper, CuO, MgO, TiO_2, nano flyash, nanopolymer of polypropylene, MgO, zeolite, nanolime, carbon nanotubes and nanofibers, all decreased the plasticity index due to their high densities and lesser surface area than clay and silica [37,44,45,49–53]. The liquid limit of soil directly correlates to the compressibility of that soil. The high compressibility of any soil corresponds to a high liquid limit. The increase in liquid limit could be due to the water absorption capacity of added nanoparticles. Such variations in the results may occur due to the dissimilarities in the soil origin, deposit and type. Therefore, during conducting the experiments, any experimental error, factor and correction must be taken care of.

4.2 Compaction properties

Research conducted using copper and alumina nanoparticles showed that high density copper nanoparticles increased the maximum dry density but, high dosage of nanoparticles started to agglomerate, which caused an increase in void ratio and a decrease in the dry density of soil. Copper nanoparticles agglomerate less than alumina, because copper nanoparticles are about 2 times bigger in size than alumina [45]. TiO_2, nano flyash, nanoclay and nanoparticles also have the same effects on compaction properties [48,51]. An increase in maximum dry density could be an effect of rearranging and cementation between soil particles. Nanoclay showed the reverse effect on silty clay i.e., a decrease in maximum dry density and increase in optimum moisture content have been reported. A probable reason for decreased dry density was flocculation and agglomeration of soil particles and cation exchange reaction. But sometimes, lesser specific gravity and pozzolanic reactions could also be the reasons for the reverse effects [37,52,54,55].

4.3 Strength properties

Nanomaterials improved the strength characteristics of various types of soils up to a satisfactory level. Nano-Z solution increased the CBR strength of soil by forming the siloxane bonds. These bonds are similar to natural primary valence bonds found in the soils. Nano sized additives fill the voids faster and behave like a sealant in the soils. This hydrophobicity in the soils is created by long alkyl chains. These chains help to adsorb the water from soil voids and consequently decrease the plasticity of the soil. Thus, an ion change mechanism in the soil ultimately produces hydrophobic material [50]. 3% of nanosilica has improved the CBR of the lime stabilized clay. The amount of nanosilica in the range of 0.7% is found as optimum because beyond this, the benefits of nanosilica become limited [56,57]. Nanoclay is also found excellent stabilizer for fine grained soils when used at 1.5% by weight of dry soil [58,59]. It also increases the shear strength and decreases the angle of refraction when mixed in the silty soil [55,60]. But, freeze and thaw cycles decrease the compressive strength [61]. Nano particles have a positive effect on the thixotropy of the soil. Thixotropy is the property of the soil by which soil regains strength without any moisture change and is very important to be known by geotechnical engineers [48]. Nanosilica in the range of 0.7% adversely affects the strength properties of the soil and this amount can be considered as optimum. The micro imaging of the soil samples also confirmed the absorption of water in the matrix [57]. The improvement in the strength of the cement treated soil could occur due to an increase in the hydration process. Pozzolanic effects, crystallization and filling effects can also be other reasons for the strength gain in the soils [62]. Calcium silicate hydrous (CSH) gel formation with calcium hydroxide $Ca(OH)_2$ was also observed through scanning images. However the formation of $Ca(OH)_2$ is not good for strength properties of the soils. Nanoparticles in the cement treated soil infuse like an atom and generate the prevailing linkage between particles. This infusion becomes easy due to a larger specific surface area and higher specific energy. Moreover, beyond the optimum amount, the reactions reverse and generate a high amount of calcium hydroxide which weakens the bonding and imparts the cracks in the soil specimens. Colloidal silica grouting arrests the liquefaction in the soils. Various researchers suggest to use 5%-20% colloidal silica [10,63,64]. In the case of sand, void fillers relocate the sand particles and prolong the development of pore pressure in the media [65]. Nanoclay contains a larger specific area than nanosilica and consequently can be considered as much better for collapsible soils. Interlocking effects and chemical reactions are also other effects of nanoclay.

4.4 Hydraulic conductivity

The hydraulic conductivity of soil is very close to permeability and therefore, is an important property of the soil when the soil is to be used for lining purposes or when applied as an impermeable layer. Experiments conducted on sand grouted with colloidal silica show that the grouting material reduces the hydraulic conductivity. On a graph, this decrease followed an exponential curve. Such property of a nanostructure could be beneficial for barrier systems [65]. Bentonite soil specimens of low concentration have proved more resistive than high concentration bentonite specimens. This proves that low bentonite content can be used where no effect of bentonite is to be considered [45]. Nano CuO and γ-Al_2O_3 particles clogged the voids in clayey soil specimens and hence reduced the hydraulic conductivity of the specimens. Nano cloisite showed an inverse relationship with hydraulic conductivity [35,61]. Nano structured multiwall tubes and carbon nanofibers both also were found excellent in decreasing hydraulic conductivity. Surprisingly, nanoiron particles did not show any noticeable variation in the hydraulic conductivity of the fine soils [66]. This all happened due to the blocking phenomenon which restrains the flow to maintain uniformity while another phenomenon ripening is related to a decrease in porosity and permeability [53]. Bentonite, nanoclay, nanoalumina also has no significant effect on hydraulic conductivity but decrease the desiccation cracks in the soil. This property of the materials can be used during the lining of canals [44]. Nanosilica of sizes i.e., 15 nm and 80 nm, decreased the hydraulic conductivity and, 15 nm nanosilica was found more effective than 80 nm due to their higher particle density [67]. Nano particles of more than 0.8% increased the hydraulic conductivity due to the adsorption of more water. Moreover, nanoparticles in excess quantity, agglomerate and leave the voids behind consequently triggering the water movement through the media and increasing the permeability.

4.5 Consolidation and shrinkage

Consolidation is a natural process, in which soil voids change gradually under pressure over time. This property of fine-grained soils has its own pros and cons. Sometimes, consolidation is good for compaction purposes while on the other hand consolidation could be disastrous when the foundation of the superstructure gets settled. In the row, iron oxides and allophone clays reduced the consolidation settlement [68]. Nano particles of TiO_2 and flyash reduced the consolidation characteristics of soft soil. Both additives reduced the consolidation settlement by 60% and 67% respectively [51]. Nanoclay, NanoMgO, Nanoalumina were also found very effective in reducing the consolidation settlement by about half and increasing the load carrying capacity by almost by 50%-60% [48,69,70]. Generally, consolidation settlement is less under loading conditions, when nanoparticles are added to the soil. Because water gets replaced by the nanoparticles and increases the density of the treated soil. Moreover, the remaining water could be utilized during ion exchange which is instant after adding the additives. Research proves that 0.7%, 0.3% and 0.2% are the optimum amounts of NanoCuO, NanoMgO and Nanoclay to improve the strength properties of organic soils. Polypropylene homopolymer eliminates the swelling behavior of clayey soils. This is due to hydrophobic nature imparted by the fibers in the soils. Nanoclay also has the same effects on fine-grained soils [37,62]. Nanoparticles are not cost-effective so, their use in commercial applications is still questionable. Further research to explore the toxicity spreading in the field is also a concern [71].

4.6 Field applications

A limited number of studies have been conducted on the field testing and applications of nanoparticles' treated soils. The primary reason for the limited utilization of nanomaterials at construction sites is a lack of fundamental knowledge in mixing, testing, and assessing their performance. However, sand stabilized with Nanosilica is in use. This all is made possible by the fact that in nanosilica treated sands, the reactions can be controlled at the field by adjusting the pH and salt concentrations of the silica solution. Colloidal silica has a unique property to alter its viscosity by adjusting pH and ionic content. Although, limited pressure application restricts its use in sands [72]. Reduction in hydraulic conductivity is a benefit of colloidal silica. This provides a sealant against permeability and capillary action in soils [73]. Reduced hydraulic conductivity can be utilized in preventing water leakage through strata, foundation and underground structures. Nanoparticles are good enough to reduce the plasticity index and crack propagation in the dam embankment [33,61]. Since colloidal silica matrix is highly impermeable, this property of colloidal silica can be utilized in the lining of sanitary landfills to prevent the spread of toxicity to the nearby unpolluted areas [72].

5. Conclusions

The present article contains the information on fundamentals, mechanisms and benefits of nanoparticles mixed with a variety of soils. After a thorough study, it is concluded that there is a significant gap in the factual reaffirmation and consistency of the results in this area. Though laboratory results showed that just a small amount of nanomaterial can change the soil properties unexpectedly field applications of the research work are barely seen. The astonishing results of nanomaterials are due to their high reactivity. The reactivity has been imparted by their high surface areas and surface charges. Mixing methods of nanoparticles is also a factor for their reactivity. The addition of nanoparticles improved the plastic, strength, and shear hydraulic properties of various soil types if used in optimum quantity. Beyond optimum, the result can get worse. The improved properties have wide applications in pavement construction, water water barriers, embankments, landfilling and water retaining structures. The mechanism of nanomaterials is controlled by the form in which they have been used i.e., to avoid the flocculation of nanomaterials, they must be used in colloidal form rather than powder form.

Future scope

Given the consistent and dependable outcomes generated by nanoclay, it is advisable to promote research endeavours that aim to reduce the utilization of other nanomaterials such as Nanocopper, Nanoalumina, Nanomagnesia, and the like.

It is imperative to ensure that both experimental and numerical studies are aligned with real-world field applications, thereby enhancing the practical relevance of the research.

The integration of systematic and optimization tools should be advocated for further substantiating and validating the optimization processes.

Future research endeavours could yield valuable insights by exploring a diverse array of soil types and various nanomaterials, thereby expanding the scope and depth of our understanding of this field.

Author Contributions

Amit Kumar: Conceptualization and supervision. Amit Kumar and Kiran Devi: Methodology, Data curation, Original draft preparation, Visualization, Investigation, Paper Writing and Editing.

Conflict of Interest

The authors declare that there is no conflict of interests concerning the publication of this manuscript.

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Data Availability Statement

The authors declare that all data supporting the findings of this study are available within the article.

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