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REVIEW PAPER

A Review: Influence of Potential Nanomaterials for Civil Engineering Projects

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Abstract

The construction industry is increasingly turning to use of environmentally friendly materials in order to meet the sustainable aspect required by modern infrastructures. In the last two decades, the expansion of this concept and the increasing global warming have raised concerns on the extensive use of Portland cement and fly ash due to the high amount of carbon dioxide gas associated with their production. The development of nanotechnology and nanomaterials offers promising signs for a change in the way of construction and geotechnical projects. The aim of this research is to show potential of nanomaterials to replace traditional materials for civil engineering to optimize construction projects, i.e., to reduce global warming by using less amount of cement or fly ash, and finally drop cost of projects. The incorporation of variously manufactured nanomaterials into the matrices of conventional construction materials leads to drastic advancement in vital characteristics including mechanical strength, fatigue and damage resistance, durability, and lightness. However, due to the significance and serious disadvantages of using traditional materials like lime, cement, and fly ash as soil stabilizers, finding alternative additives is a matter of sustainability for construction projects.

Keywords Nanomaterials · Microscopy techniques · Stabilization · Construction projects

1 Introduction

The application of nanotechnology in various applied fields is receiving widespread attention. Nanotechnology is the re-engineering of materials and devices by controlling the matter at the atomic level. In other words, nanotechnology is a field that is led by the developments in basic chemistry and physics research, where the knowledge of atomic and molecular levels is used to produce materials and structures that achieve tasks that are not achievable using the materials in their classic macroscopic form Roco et al. (1999) and Chong and Garboczi (2002). A precise definition of nanotechnology was suggested by Drexler, as the product with dimensions between 0.1 and 100 nm (Drexler 1981). For visualization, a DNA double helix has 2 nm diameter and strand of human hair has 80,000 nm thickness. It is estimated that the products and services associated with nanotechnology will reach 1,000,000 million Euro per year after 2015 (Pacheco-Torgal and Jalali 2011; Sparks 2017). RILEM TC 197-NCM, "Nanotechnology in Construction Materials," is the first document that clearly discussed the potential of nanotechnology in the field of construction and building materials, namely:

- The use of nanoparticles, carbon nanotubes, and nanofibers to enhance the strength and durability of cementitious composites, and pollution reduction.
- Production of corrosion stainless steels.
- Production of thermal insulation products.
- Production of coats and thin films with the ability of self-cleansing and self-color adjustment to reduce energy consumption.

On nano-level, gravity becomes negligible; thus, irrelevant, electrostatic forces dominate, and quantum effects arrive in, as particles become nano-sized, the proportion of atoms on

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the outer surface relative to those inside increases, and this results in different properties. Researchers working on nanoscience and nanotechnology are exploring these novel properties to change the macro-properties and create appreciably new materials and processes. Study of the Canadian Program on Genomics and Global Health (CPGGH) states that nanotechnology in civil engineering is among of ten applications that are likely to have an effect in the developing world (Zhu et al. 2004; Rana et al. 2009). Basic sciences are related to the composition, fundamental properties, structure, and interrelationships of matter, while engineering deals with the application of these principles. Chemistry and physics usually focus on smaller scales to allow more detailed and precise information of the matter, whereas engineering typically focuses on the scale where the matter works jointly to achieve a certain function (e.g., soil–cement, concrete road pavement, or building). Due to the mentioned significance and serious disadvantages of using traditional materials like lime, cement, and fly ash as soil stabilizers, finding alternative additives is a matter of sustainability. Evaluating the different viewpoints, it can be theorized that nanotechnology can possibly play an important role in the enhanced use of existing and available materials in construction projects. In terms of the need for sustainable construction projects, the main novelties of the additives' agent are as follows:

- Reducing the use of natural resources
- Minimizing energy consumption
- Minimizing emission of greenhouse gases—controlling pollution of air, water, and earth
- Raising the level of safety and risk prevention, and
- Providing an elevated level of user comfort and safety

Finally, the main objective of this study is to show the potential of nanomaterials as stabilizing agents for construction projects.

2 Typical Nanomaterials

According to Taha and Taha, the soil–nano-alumina mixtures brought the beneficial changes in the soil properties (i.e., compaction characteristics, volumetric expansive strain, the crack intensity factor, and volumetric shrinkage strain). These changes are mostly due to the displacement and rearrangement of soil particles by the addition of nano-alumina (Taha and Taha 2012).

Azzam defined that the resulting in nanocomposites acted as nanofiller materials which decreased the plasticity and compressibility parameters of the treated clay. The initial structural analysis helped in a better understanding of the modified microstructure and the measured size of induced nanocomposites. The constructed inclusions fill the inter-assembling pores thus notably producing a higher vertical effective yield stress which again reduced the volumetric shrinkage and created isotropic and compressible materials to a lesser extent of desiccation cracks. It also increased the tensile and the shear strength of the stabilized clay with an increase in the nanocomposite size. This technique can be effectively used for road embankments and slope stabilization (Azzam 2014).

Organic nano-polymers and their mixtures are used as stabilizing agents. Several researchers investigated aqueous polymer applications, while others provided valuable data on the nano-polymer–soil interactions that define the effectiveness of nano-polymer solution in various applications. However, this terminology of using a chemical point of view of nanocomposites was accepted in stabilizing swelling soil by the polymer technique, as discussed by Azzam (2012). The modification of the clay microstructure was done with the use of polymers to produce nanocomposite materials with components of clay (Fig. 1).

Figure 1 shows that polymer can be distributed in clay matrix as a filler with clay particles, changing the clay microstructure and creating nanocomposites which are chemically explained by organic onium and ion change process. Polymers were used in a number of applications to improve and reinforce several material properties (Onyejekwe and Ghataora 2015; Azzam 2012; Naeini et al. 2012). Polymers can be reinforced with different fillers to develop the surface textures. The most common nano-sized fillers are carbon nanotubes, nano-sized particles, and intercalated layers. Since nanoparticles have significant surface area and quantum effects, their incorporation in a polymer matrix enhances several material properties. In common, the microstructures of clay/polymer nanocomposites are classified according to the level of intercalation and exfoliation of polymer chains into the clay galleries (Naeini et al. 2012; Guo 2014; Salvetat et al. 1999; Kiliaris and Papaspyrides 2010).

Azzam studied the microstructures of stabilized clay soil to disclose the effect of constructed nanocomposites/nanofillers through the internal voids of normal clay soil, and it reduced and mitigated the vertical strains at a high-stress level (Figs. 2, 3) (Azzam 2014).

Figure 2 shows the SEM image of the natural clay fabric or clay microstructure which delivers the orientation and arrangement of the clay skeleton. The spatial distribution of the solid particles and the particle-to-particle relationship were witnessed. Aggregation and clay matrix was created, and inter-assembling voids were observed. The microfabric of the sample at a magnification range of 1000× includes highly dense clay matrices with disturbed parallelism containing very small inter-assemblage pore spaces and big inter-assemblage pore spaces of various shapes.

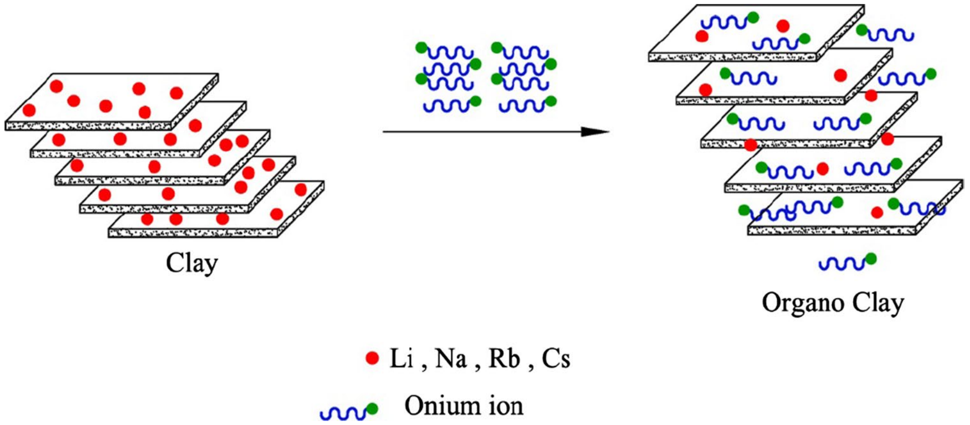


Fig. 1 Scheme of the modification of clay layers by organic onium cations and ion change process (Azzam 2014)

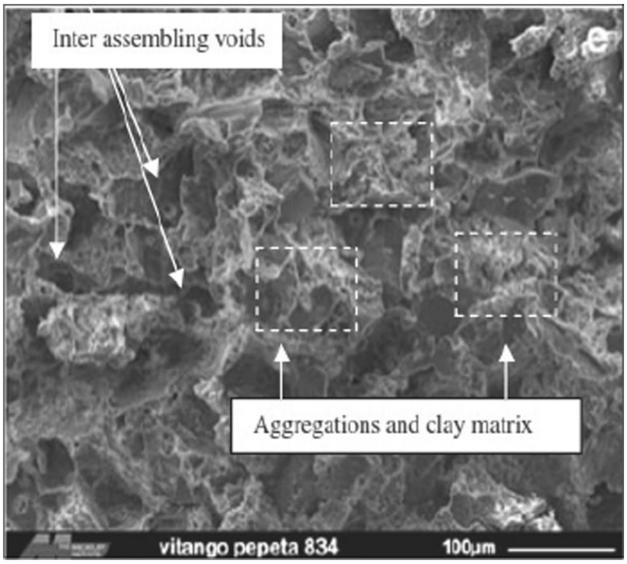


Fig. 2 SEM image of tested clay without stabilization (Azzam 2014)

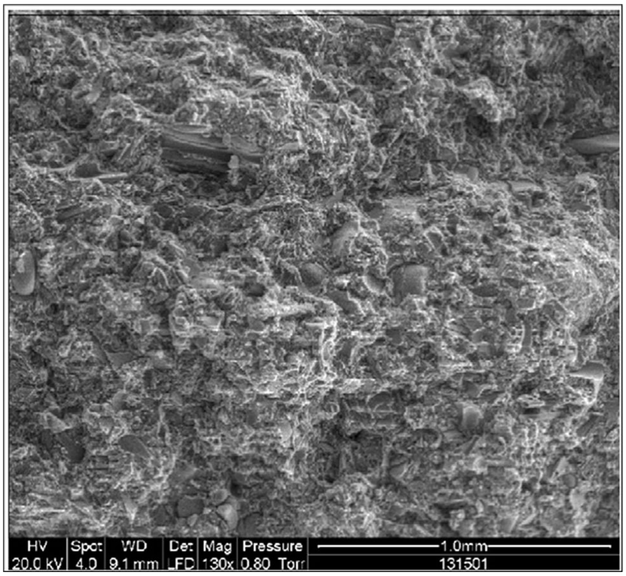


Fig. 3 SEM image of the fractured surface of a clay–polymer–nanocomposite (at polymer concentration 10%) (Azzam 2014)

Figure 3 shows the SEM image of the modified clay at a polymer concentration of 10%, which appears to be an aggregate of platelets exfoliated through dispersion in the polymer during the sample preparation. It has been observed that addition of polymer to clay modifies the microstructure fabrics due to the induced nanocomposites, and polymer raises the field density due to the filling of pores; thus, the pores spacing decreases within the clay matrix. The polymer was dispersed in the clay matrix in aggregates of different sizes; this indicated the consistent distribution of polymer within the clay sample. The polymer stabilization increased the net electrical attraction between neighboring grain particles. It also improved the grain surface of the tested clay against water by constructing the nanocomposites which fill the voids. When the polymer is mixed with clay samples, the extra water can be efficiently absorbed as justified by the reduction of the optimum moisture contents (OMC).

Burke et al. (2014) presented a new application of titanium oxide nanoparticle where it used as a treatment against ultraviolet spectroscopy (UV) and aging deterioration of bituminous binders. Their analyses revealed that low rates of nano-sized can affect the aging of bitumen positively. The effect powders on the stiffness of the binder require being evaluated, as the introduction of the nanoscale powders stiffens up the binder significantly (Paul and Robeson 2008). Yang and Tighe evaluated the influence of and ZnO on the potential aging of bitumen binder. Various contents were added to bitumen and applied to the surface of asphalt slabs. These slabs were subjected to direct sunlight for a longer period to permit potential aging in the binders. Analysis of the temperatures recorded below the applied bitumen layers hinted that the temperature under the untreated section was on average higher than that under the ZnO treated section, thus resulting in lower aging rates (Peponi et al. 2014).

Numerous researchers evaluated the influence of nano-clay on asphalt mixture, and they found that nano-clay can substantially improve the mixture properties (Shunmugasamy et al. 2015; Burke et al. 2014; Yang and Tighe 2013; Arabani et al. 2015; Walters et al. 2014). Nano-clay makes the clay complexes well matched with organic monomers and polymers. These nanocomposites comprise one or more polymers with layered silicates having a layer thickness in the order of 1 nm. Common clays are natural minerals and are subjected to natural dissimilarities in their formation. Nano-clay with the big active surface area (up to 700–800 m^2) helps to have an intensive interaction between the bitumen and the nano-clay. The appropriate selection of treated clay is essential to ensure effective penetration of the polymer into the clay interlayer spacing and thus resulting in the required exfoliated or intercalated product. In intercalate structure, the organic component is filled between the clay layers in such a way that the interlayer spacing is extended, but the layers still bear a definite spatial relationship with each other. However, in an exfoliated structure, the layers of clay are entirely separated and the individual layers are spread all through the organic matrix. Different physical properties (tensile strength, flexural strength, tensile modulus, stiffness, and modulus thermal stability) of the bitumen can be improved when it is modified with small amounts of nano-clay. Usually, the elasticity of the nano-clay bitumen is higher and the dissipation of mechanical energy much lesser than in the case of unchanged bitumen (Kavussi and Barghabani 2014; Faruk et al. 2014).

Cui et al. showed that addition of CNT to concrete increases the hydration rates and stronger bonds build up between the CNT and the cement paste, while Petrunin et al. recorded that the increases of 70% in the compressive strength of CNT reinforced concrete and reduction of 12% in the heat conductivity. Moreover, most properties at the microscale remain approximately the same as those of the bulk materials. The reduction in one or more geometric dimensions down to the nanoscale totally modifies the performance of the material. Thus, high surface-to-volume ratio and cation exchange capacity exist at the nanoscale (Hamzah et al. 2015; Santagata et al. 2015; Yusoff et al. 2014). Nanoparticles interact vigorously with other particles and solutions, and very little amounts may lead to substantial effects on the physical and chemical properties of a material. Gravitational force at the nanoscale can be disregarded; instead, electromagnetic forces are dominant. Firoozi et al. studied an assessment of nano-zeolite on soil properties. They found that the liquid limit increased with the difference of percentage of nano-zeolite, while the curve of plastic limit increased until 0.5% percent of nano-zeolite after 0.5% the behavior changed to increase. Reductions in the plasticity indices are indicators of soil improvement (Firoozi et al. 2014a).

Hung and Wang (2016a) investigated the potential benefits of nanotechnology for innovative solutions in the soil improvement sector. They showed that soil improvement based on nanomaterials causes only slight ground disturbance, is environmentally friendly, and is economical compared with traditional grouting methods. The application of nanomaterials in geotechnical engineering has advantages both for the development of nanomaterials and the optimization of soil properties. Furthermore, Hung and Wang (2016b) studied laboratory investigation of liquefaction mitigation in silty sand using nanoparticles. They found that the rheological properties of a sol–gel transition in a laponite suspension improve the liquefaction resistance, while at the same time its "thinning behavior" reduces the liquefaction resistance at higher cyclic loading. Also, they showed that the liquefaction resistance of the laponite–silt samples is stronger than that of the pure silt samples. The pore pressure accumulation process in the treated samples is delayed, and the deformation is much smaller compared with that of the untreated samples. Finally, Hung et al. (2019) examined centrifuge testing of liquefaction mitigation effectiveness on sand foundations treated with nanoparticles. They showed that the laponite (a clay nanoparticle) caused reduction in excess pore pressure and settlement.

3 Mixing of Nano-sized Powders

A novel method for mixing nanomaterials with soil was studied by Firoozi et al. (2019). They examined the horizontal ball mill mixing of nano-copper oxide with kaolinite (Fig. 4). Ball milling parameters (rotation speed, the weight ratio of balls to powder and milling time) of the planetary ball milling were optimized for proper mixing of nano-copper oxide and kaolinite powder (Fig. 5 and Table 1).

In addition, their results showed that increase in mixing time decreased the agglomeration of nano-copper powders and kaolinite and increased the homogeneity of nano-copper powder with kaolinite particles (Fig. 6). The quality of mixing was assessed through intensity and scale of segregation using concentration data obtained through energy-dispersive X-ray spectroscopy (EDS) and X-ray diffraction (XRD) analyses. It was observed through these two tests that increase in ball milling time after 6 h resulted in grain size reduction. Field emission scanning electron microscopy (FESEM) analysis showed that nano-coppers were regularly found on the surface of kaolinite particles after 6 h of horizontal milling at 4:1 ratio of balls to the powder mixture. Furthermore, 24-h mixing resulted in grinding of kaolinite particles and hence their size was reduced. Particle size analysis confirmed these results as well.

Fig. 4 Horizontal ball mill mixing of nano-copper oxide with kaolinite (Firoozi et al. 2019)

4 Characterization of Materials

Precise characterization of materials is important in order to assess their anticipated behavior and properties, particularly if these materials are nano-sized or if their macroscale properties are alike and understanding of their nanoscaled properties is necessary to apply them effectively in soil mechanic. Normally, traditional engineering tests and properties do not adequately distinguish between different materials. Typical nanotechnology instrumentation as shown in Figs. 7, 8, 9, 10, 11, 12, 13, 14, 15, and 16 includes imaging techniques such as the scanning electron microscope (SEM), atomic force microscope (AFM), analysis techniques such as X-ray diffraction (XRD), transmission electron microscopy (TEM), photon correlation spectroscopy (PCS), nanoindentation, Mastersizer, and zeta potential. It is important to consider the type of information desired as well as the needed resolution before a specific technique is chosen (Cui et al. 2015; Petrunin et al. 2015; Shah et al. 2014). Sobolev and Shah (2015) mentioned that characterization techniques can be separated (based on the needed information and resolution) into morphology (nano-structure architecture), crystal structure (thorough atomic arrangement contained within the microstructure), chemistry (elements present), and electronic structure (nature of bonding between atoms). Microscopy techniques on hand for characterization consist of various types of electron microscopy. These include TEM, SEM (used for examination and analysis of surface and subsurface nano-structured system), and scanning transmission electron microscopy (STEM) (analysis of the bulk structure of thin sample). Scanning probe techniques such as AFM are used to study the surface characteristics of a specimen through magnitudes of atomic forces. SEM can be employed for resolutions of down to 1, and AFM can offer a resolution of down to 0.1 nm (Sobolev and Shah 2015; Firoozi et al. 2014b, 2015; Lin et al. 2014).

5 Effect of Nanomaterials on Environment

The effect of a variety of nanomaterials on the environment is fiercely debated in nanotechnology and environmental research. Various ongoing investigations focus on the doubt concerning the potential effects of materials that exist on the nanoscale with properties that are different than when using the material on a micro- or macroscale. Other applications of nanomaterials include disease diagnosis, alternative energy, and catalysis. Most recently, nanomaterials have effectively been used for cleanup and pollution control. However, the future for applications of nanotechnology in environmental remediation and other sectors looks bright, and the other side of nanotechnology presents scary challenges. Similar to

Fig. 5 Variable parameters and their level in design experiment (Firoozi et al. 2019)

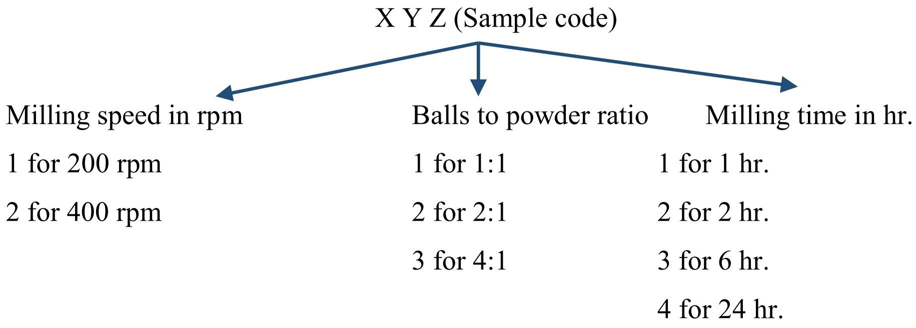


Table 1 Different conditions of designed experiment (Firoozi et al. 2019)

Nos.	Code	Mix soil amount (g)	Masses of balls (g)	Milling speed (rpm)	Duration (h)
1	111	800	800	200	1
2	112	800	800	200	2
3	113	800	800	200	6
4	114	800	800	200	24
5	121	800	1600	200	1
6	122	800	1600	200	2
7	123	800	1600	200	6
8	124	800	1600	200	24
9	131	800	3200	200	1
10	132	800	3200	200	2
11	133	800	3200	200	6
12	134	800	3200	200	24
13	211	800	800	400	1
14	223	800	1600	400	6
15	234	800	3200	400	24

other emerging technologies of the past, nanotechnology has ignited growing public debates on environmental and health aspects of its products and services outweigh social and economic benefits (Wei et al. 2013; Xu et al. 2012; Fulekar et al. 2014; Bashir and Chisti 2017; Roco and Bainbridge 2005; Colvin 2003) with smart design and planning. Construction projects can be made sustainable and thus save energy, minimize resource usage, and avoid damages to the environment.

Principles for the application of nanomaterials in environmental pollution control and resource reutilization were studied by Yang et al. (2019). They found that the development in other novel technologies and enormous developments in nanoscience and nanotechnology have triggered a great deal of interest in environmental restoration and nanomaterials could be employed as excellent sensors, adsorbents, photo/electro-catalysts, and disinfectors. Wang et al. (2018) found that the plasmonic nanotechnology can be used for environmental applications more widely, also for soil remediation, resource recovery during waste treatment processes, and detection of contaminants. In addition, the

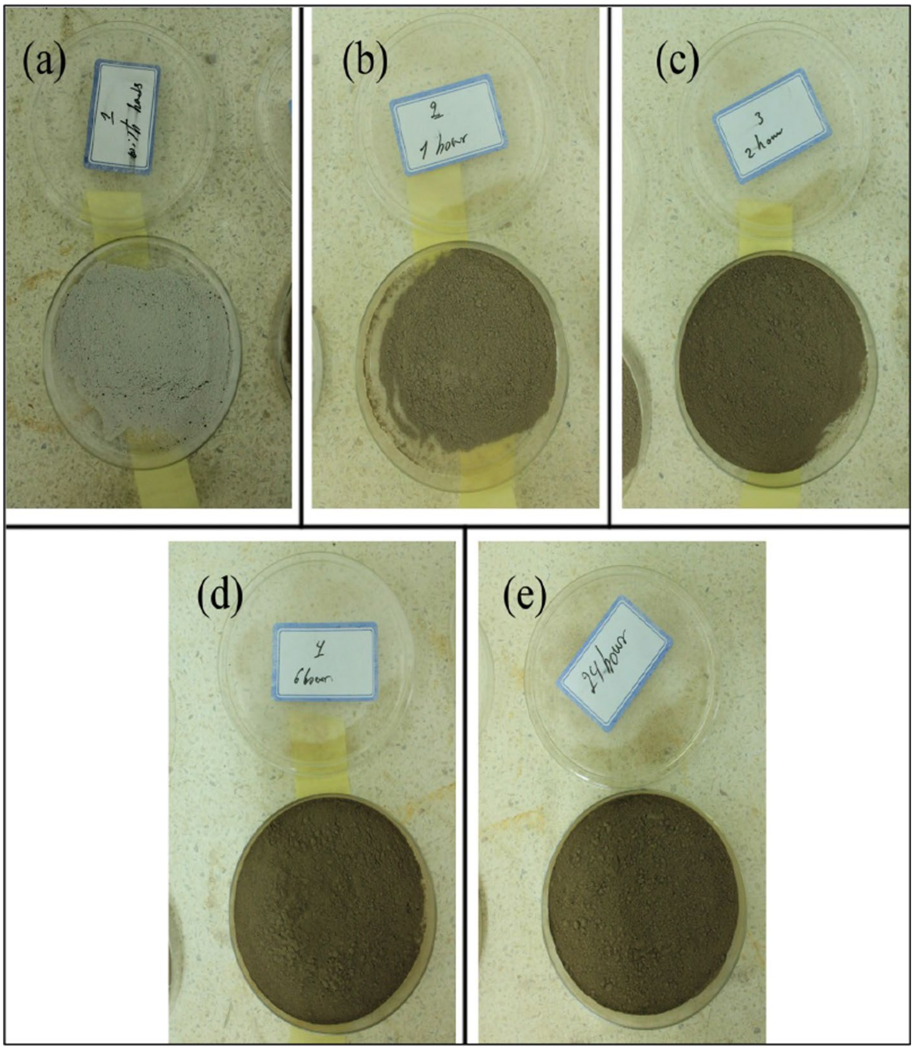


Fig. 6 Images of the samples during milling (Firoozi et al. 2019)

Fig. 7 Preparation of samples for FESEM

toxicity of engineered plasmonic nanomaterials, the possibility of their release, fate, and transformation, in the environment and subsequent impact on the health of ecosystem, are also addressed in detail. Finally, novel nanomaterials with excellent sorption capacities, mild stability, and environmental-friendly were studied by Wu et al. (2018). They showed that the applications prospect of novel nanomaterials (e.g., MOFs, nZVI, MXenes, and g-C_3N_4) in removing heavy metal ion polluted water.

6 Nanomaterials and Costs

The costs of the most nanomaterials and apparatuses are comparatively high. This is due to the new technology and the complexity of the equipment used for the preparation and characterization of the materials. However, costs have been seen to decrease over time and the prospects are that, as manufacturing technologies get better, these costs may further reduce. Either the predicted decrease will make the materials as run-of-the-mill construction engineering materials yet to be seen and largely depends on the benefits rendered through the application of these materials. Present opinion is that in particular cases, the materials will allow unique solutions to complex problems that cause them to be cost-effective, which will lead to large-scale application of these specific technologies. In other cases, the conventional methods for treating the problem may still stay the most cost-effective. The challenge to the construction engineer is to solve real-world transportation infrastructure problems and offer a facility to the general public at a practical cost.

7 Conclusion

Nanotechnology has the potential to be the key of brand new world in the field of soil mechanics and construction materials. Although replication of natural systems is one

Fig. 8 Instrument FESEM

of the most promising areas of this technology, scientists are still trying to grasp their astonishing complexities. Furthermore, nanotechnology and nanomaterials are a swiftly growing area of research where new properties of materials on the nanoscale can be utilized for the benefit of construction infrastructure and a number of capable developments exist that can potentially modify the service life and life-cycle cost of construction infrastructure to make a new world in the future. Based on the information and arguments in this research paper, the following conclusions can be made:

- The application of nanotechnology and nanomaterials growths in the field of civil engineering can potentially lead to advances in solving general engineering problems;
- Most of these applications, however, first need to be scaled to the dimensional applications that are typical for the geo-environment;
- The technical and cost-effectiveness of available technologies should both be evaluated as part of the evaluation of nanotechnology solutions in engineering;
- Fundamental research into the properties of engineering materials to improve the understanding regarding their performance is an important output of nanotechnology characterization of soil stabilization; and
- The development of novel materials and the improvement of existing materials in response to the scarcity of natural materials have become a possibility through the application of nanotechnology techniques on traditional pavement materials.

Fig. 9 Schematic of atomic force microscope (AFM)

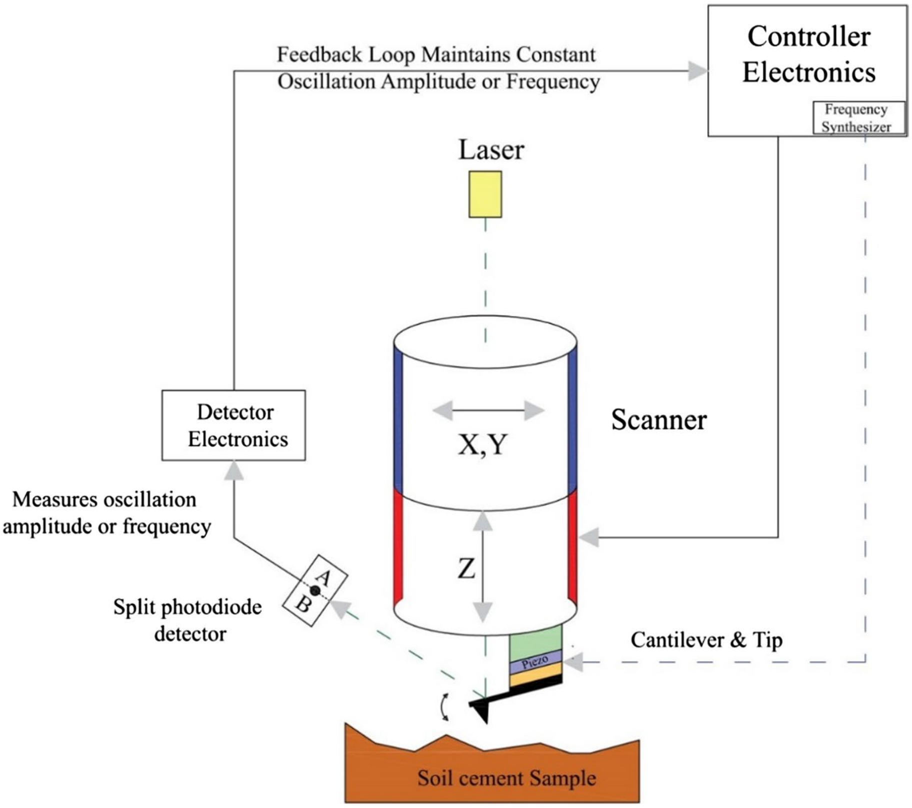
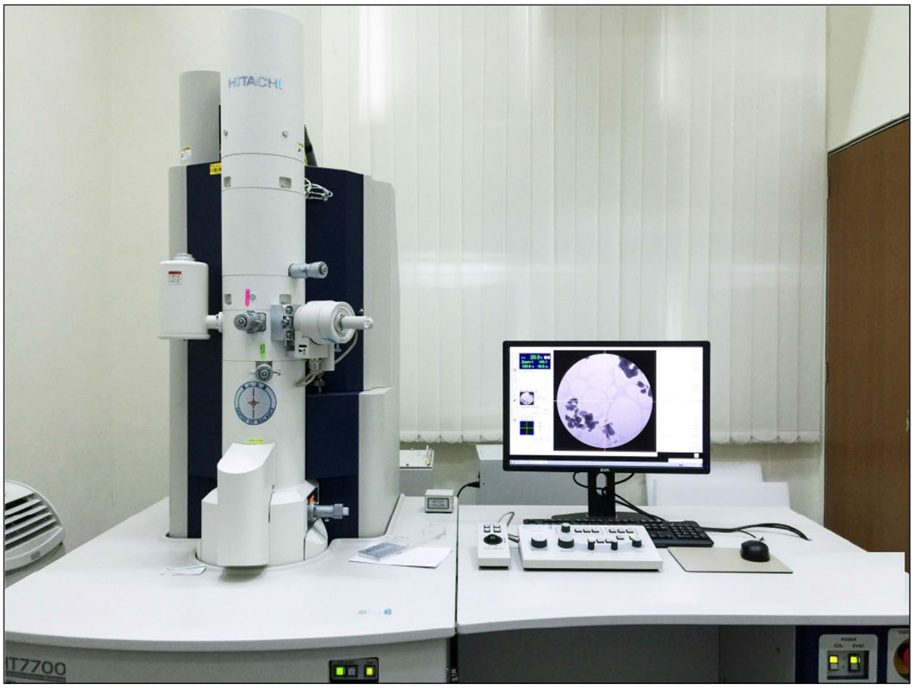


Fig. 10 Schematics of AFM equipment

Fig. 11 X-ray diffraction (XRD) equipment

Fig. 12 Transmission electron microscopy (TEM) equipment



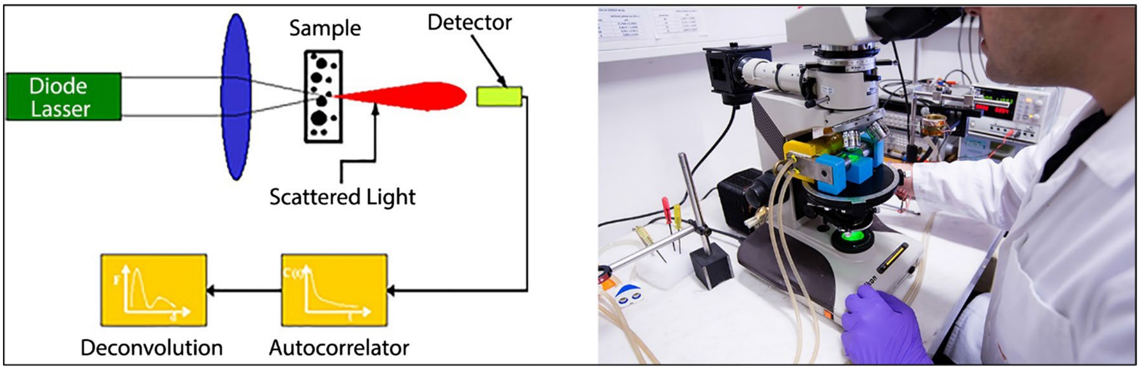


Fig. 13 Schematics of photon correlation spectroscopy (PCS) equipment

Fig. 14 Nanoindentation (TEM) equipment

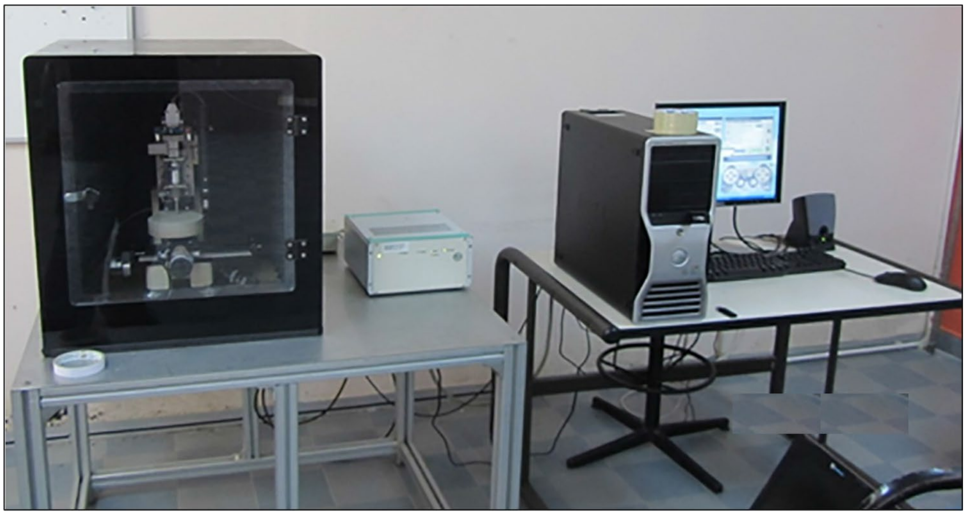


Fig. 15 Mastersizer analysis equipment

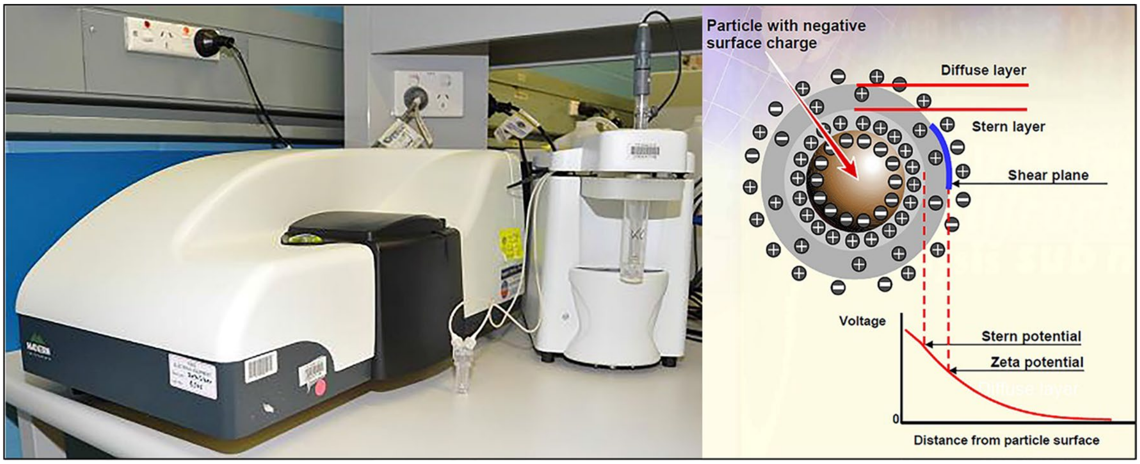


Fig. 16 Schematics of zeta potential equipment

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Compliance with Ethical Standards

Competing interest The authors declare that they have no competing interest.

Ethics Approval and Consent to Participate The presented work is part of research project entitled “Soil improvement using nanomaterials.” There is no any ethical conflict. Authors on behalf of an associated organization fully authorize to publish research.

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