Journal of Geomine (2023), 1(2), 92-102
DOI: 10.22077/jgm.2023.6759.1014

The Role of Nanoclay in the Soil Stabilization: A Short Viewpoint

Mahsa Sedighi[1,2], Hadi Farhadian[3]

Recived: 2023 Sep. 08, Revised: 2023 Oct. 18, Online Published: 2023 Oct. 29

ABSTRACT

Nanoclay, composed of phyllosilicates, exhibits unique properties due to its layered structure and its ability to swell or shrink in response to water accumulation or withdrawal. Its use in geostability involves enhancing the geotechnical properties of soils, such as reducing the plasticity index, increasing specific gravity, improving compaction, and enhancing shear strength. Additionally, nanoclay serves as a reinforcing material in polymer composites, improving their strength, toughness, durability, and barrier properties. This study provides an overview of the properties, applications, and challenges associated with nanoclay in soil stabilization. The compatibility of nanoclay with organic monomers and polymers can be modified to enhance the overall performance of nanocomposite materials. Various industries and applications utilize nanoclay for soil stabilization, including construction, agriculture, mining, and environmental remediation. However, there are challenges associated with its use, such as cost, compatibility with different soil types and stabilizers, environmental concerns, long-term durability, and health and safety risks. Future research should focus on the synthesis, characterization, and surface modification of nanoclay, as well as the effectiveness of different soil stabilization methods and potential environmental impacts.

KEYWORD

Nanoclay, Soil Stabilization, Geostability, Nanocomposites.

I. INTRODUCTION

Nanoclay constitutes a constituent comprising phyllosilicates, primarily characterized by the presence of oxygen, silicon, and other constituents, originating from natural reservoirs and subjected to prior chemical processing. It is a type of clay that has unique properties due to its layered structure. Nanoclay can swell or shrink as water accumulates or is withdrawn between its layers. This property allows it to increase in volume by up to six times when it absorbs water, forming stable gels (Abulyazied and Ene, 2021). In the context of geostability, this structure is used to enhance the geotechnical properties of soils. It can be added to clay and silt soils to improve their geotechnical properties. It helps in reducing the plasticity index, increasing the specific gravity, improving compaction, and enhancing shear strength (Khalkhali et al., 2019). Nanoclay can be used as a reinforcing material in polymer composites. When added to polymers, it enhances their strength, toughness, durability, and barrier properties (Osman et al., 2017). This structure can be incorporated into nanocomposite materials to enhance their properties. It can be modified to make the clay compatible with organic monomers and polymers, thereby improving the overall performance of the nanocomposite (George and Kannan, 2020).

Nanoclay can be used for soil stabilization in various industries and applications. It can be used in construction to stabilize soils for building foundations, roads, and other infrastructure projects. It can be added to dispersive soils to improve their strength and stability (Abbasi et al., 2018; Farzadnia and Shi, 2023; Jagadeesh et al., 2022; Kausar, 2020; Yu, 2019). Nanoclay can be used in agriculture to stabilize soils for crop production. It can be added to soft soils to improve their strength and shear resistance (Subramani and Sridevi, 2016). Also, it finds some applications in mining to stabilize soils for excavation and mining operations. It can be added to dispersive soils to improve their stability and prevent erosion (Abbasi et al., 2018). Nanoclay can be used in environmental remediation to stabilize contaminated soils and prevent the spread of pollutants. It can be added to soils to improve their strength and stability, making them less prone to erosion and contamination (Shahidi et al., 2023).

Fig. 1 illustrates the intricacies of water ingress into clay plates at an extended microlevel. The term "clay particle" denotes a cohesive arrangement of clay layers, typically comprising a maximum of four layers of crystalline water. These "clay particles" aggregate to form the fundamental units of a densely packed clay double structure, referred to as "clay aggregates". The segment of the clay particle surface that runs parallel to

[1] Department of Pharmaceutics and Nanotechnology, School of Pharmacy, Birjand University of Medical Sciences, Birjand, Iran, [2] Cellular and Molecular Research Center, Birjand University of Medical Sciences, Birjand, Iran, [3] Department of Mining, University of Birjand, Birjand, Iran
M. Sedighi: m.sedighi@bums.ac.ir

the orientation of the "clay layers" is termed the "particle face". Conversely, the region of the clay particle surface that is perpendicular to the particle face is recognized as the "particle edge". Surrounding the particle faces, diffuse double layers emerge, accompanied by water molecules adhering to them, herein referred to as "double-layer water". The water present outside of the diffuse double layers is visually represented as the "equilibrium solution" (Mašín and Khalili, 2015).

While nanoclay has shown promise in improving the geotechnical properties of soils, there are some challenges associated with its use in soil stabilization including: 1. cost: nanoclay is more expensive than traditional soil stabilizers, which can make it less cost-effective for some projects (Khodabandeh et al., 2023); 2. compatibility: nanoclay may not be compatible with all types of soils or soil stabilizers. It is important to conduct thorough testing to ensure that the nanoclay will work effectively with the soil and other materials being used (Khalkhali et al., 2019). 3. environmental concerns: some nanoclay formulations may contain toxic materials that can harm the environment. It is important to use environmentally-friendly nanoclay formulations and to dispose of any waste materials properly (Khodabandeh et al., 2023). 4. long-term durability: the long-term durability of nanoclay-stabilized soils is not yet fully understood. More research is needed to determine how well these soils will perform over time (Marjan Padidar et al., 2016). 5. health and safety: nanoclay particles are very small and can be inhaled, which can pose a health risk to workers. Proper safety measures should be taken when handling nanoclay to minimize the risk of exposure (Di Ianni et al., 2020).

The present review highlights the synthesis, characterization and surface modification strategies related to nanoclay structure, followed by a comprehensive discussion on the application of nanoclay in the soil stabilization and its effectiveness based on the type of soil and the geotechnical properties.

II. Nanoclay: Synthesis, Characterization, and Surface Modification

Nanoclay is a type of processed clay that is used in a variety of applications, including high-performance cement nanocomposites and polymer-clay composites (Farzadnia and Shi, 2023; Kausar, 2020; Shakrani et al., 2017). Nanoclays are nanoparticles of layered mineral silicates, including montmorillonite, bentonite, and halloysite nanoclays, and organoclays (Kausar et al., 2022; Peña-Parás et al., 2018). Owing to their stratified composition, these materials exhibit the capacity to expand or contract in response to the ingress or removal of water molecules within their interlayers. Consequently, it becomes feasible to augment the nanoclay's volume by a factor of up to six through water absorption, resulting in the formation of enduring gel structures (Fig. 2) (Mattausch, 2015; Shunmugasamy et al., 2015).

Nanoclay has unique physical and chemical properties, made it a valuable material for various applications, including as an adsorbent and in the production of stable gels. Physical properties of nanoclay are including layered structure with a thickness of about 1 nm and a diameter of about 50-200 nm (Hayles et al., 2017; Kausar, 2020; Nazir et al., 2016), high surface area, ability to swell or shrink as water accumulates or is withdrawn between layers, and ability to increase in volume up to six times by water absorption and form stable gels.

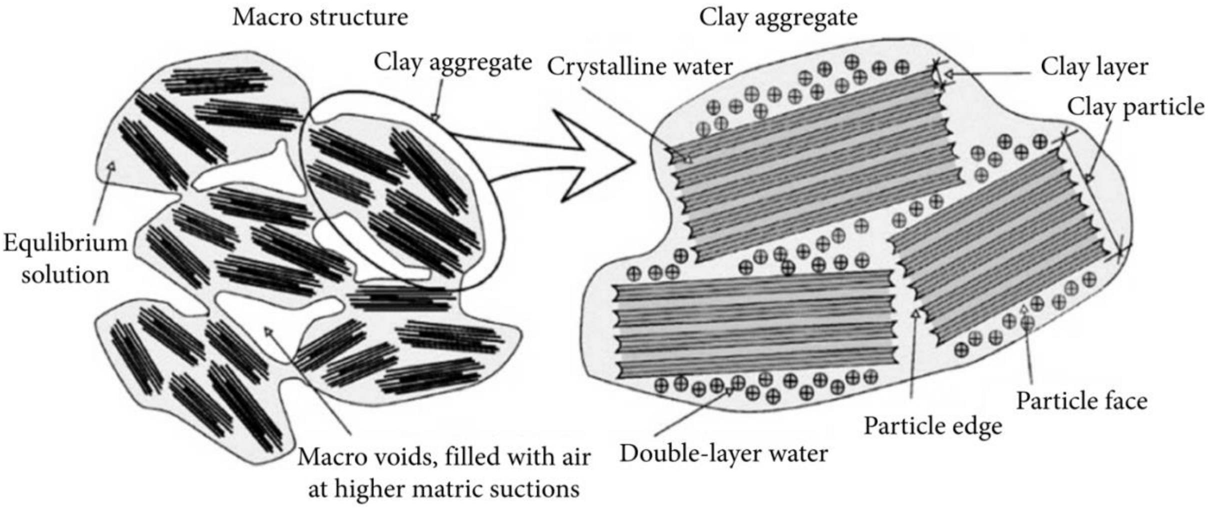

Fig. 1. The schematic representation of a densely packed clay structure, illustrating the mechanism of water infiltration into clay plates at the extended microscale, has been adapted from the work of (Mašín and Khalili, 2015).

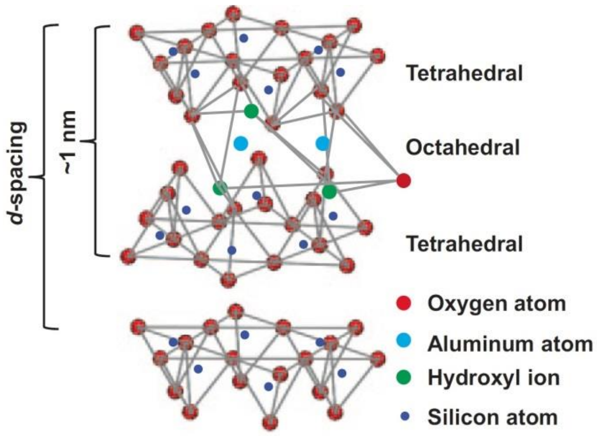

Fig. 2. Schematic presentation of the nanoclay structure (montmorillonite), adapted from (Shunmugasamy et al., 2015)

Furthermore, its chemical properties have originated from its composition composed of phyllosilicates (Hayles et al., 2017; Kausar, 2020; Nazir et al., 2016; Zaferani, 2018). It can contain different groups of minerals, including talc, mica, kaolin, montmorillonite, serpentine, and sepiolite (Shunmugasamy et al., 2015) and variations in both the dimensions and the sequential arrangement of regions where SiO4 tetrahedra are oriented either in an upward or downward configuration within the layers (Shunmugasamy et al., 2015). It can also be used as an adsorbent and produce a variety of minerals (You et al., 2011).

Various approaches are available for the synthesis of nanoclay, including solution-blending, melt-blending, and in-situ polymerization (Guo et al., 2018). The solution-blending method involves the mixing of nanoclay with a polymer solution, followed by solvent evaporation. The melt-blending method involves the mixing of nanoclay with a molten polymer, followed by cooling and solidification. The in-situ polymerization method involves the polymerization of monomers in the presence of nanoclay, leading to the formation of nanoclay-polymer composites (Albdiry et al., 2013; Guo et al., 2018; Perera et al., 2023). The most commonly used synthesis methods for nanoclay include:

1. Melt blending method: In this method, nanoclay is mixed with a molten polymer, followed by cooling and solidification. This method is suitable for large-scale manufacturing but may result in poor nanoclay dispersion compared to other synthesis methods (Guo et al., 2018).

2. Solution blending method: The solution blending method involves the mixing of nanoclay with a polymer solution, followed by solvent evaporation. This method can provide better clay dispersion due to low viscosity and high agitation power. However, it is a more complex process (Guo et al., 2018).

3. *In-situ* polymerization method: In the *in-situ* polymerization method, nanoclay is synthesized simultaneously with the polymerization of monomers. This method involves the polymerization of monomers in the presence of nanoclay, leading to the formation of nanoclay-polymer composites. It offers control over the dispersion of nanoclay in the polymer matrix (Guo et al., 2018).

These synthesis techniques possess inherent merits and demerits, with the selection of a method contingent upon the particular application and the desired characteristics of the nanoclay-incorporated material (Guo et al., 2018). When selecting a synthesis approach for nanoclays, the key factors to consider are desired properties, scalability and cost-effectiveness, and compatibility with the polymer matrix. The synthesis approach should be chosen based on the desired properties of the nanoclay, such as aspect ratio, surface area, and interlayer spacing. Different synthesis methods can result in nanoclays with varying properties, which can impact their performance in polymer composites (Guo et al., 2018). The synthesis approach should be scalable and cost-effective, especially for industrial applications. Methods that require complex equipment or involve multiple steps may not be suitable for large-scale production (Guo et al., 2018). Furthermore, the synthesis approach should be compatible with the polymer matrix in which the nanoclay will be incorporated. For example, *in-situ* polymerization methods may be more suitable for synthesizing nanoclays for polymerization reactions, while solution-blending or melt-blending methods may be better for thermoplastic polymers (Guo et al., 2018).

The synthesis technique can affect the properties of the resulting material improvement of mechanical properties, thermal stability, and barrier properties. The use of nanoclays in polymer composites can lead to improved mechanical properties, such as increased tensile strength, modulus, and impact resistance. The synthesis technique can influence the dispersion and interfacial adhesion of the nanoclays, which in turn, affects the mechanical properties of the resulting material (Fakhreddini-Najafabadi et al., 2021). Nanoclays can improve the thermal stability of polymer composites by acting as a barrier to the diffusion of heat and gases. The synthesis technique can impact the aspect ratio and interlayer spacing of the nanoclays, which can further enhance their thermal stability (Fakhreddini-Najafabadi et al., 2021). In addition, the use of nanoclays in polymer composites can improve their barrier properties, such as gas permeability and water vapor transmission rate. The synthesis technique can influence the dispersion and orientations of the nanoclays, which can in turn, affect the barrier properties of the resulting material (Fakhreddini-Najafabadi et al., 2021).

To assess the physical and chemical attributes of nanoclay, a range of methodologies is available, encompassing x-ray diffraction (XRD), transmission electron microscopy (TEM), scanning electron microscopy (SEM), fourier-transform infrared spectroscopy (FTIR), and thermogravimetric analysis (TGA) (Azzam et al., 2013; Guo et al., 2018). XRD is a technique used to determine the crystal structure and orientation of nanoclay. It provides information on the interlayer spacing and the degree of crystallinity of nanoclay (Das et al., 2015). TEM is a technique used to visualize the morphology and size of nanoclay particles. It provides high-resolution images of the nanoclay structure and can be used to determine the particle size and shape (Das et al., 2015; Peña-Parás et al., 2018). SEM is a technique used to visualize the morphology and size of nanoclay particles. It provides high-resolution images of the nanoclay structure and can be used to determine the particle size and shape (Das et al., 2015; Peña-Parás et al., 2018). FTIR is a technique used to identify the functional groups present in nanoclay. It provides information on the chemical composition and structure of nanoclay (Peña-Parás et al., 2018). TGA is a technique used to determine the thermal stability and decomposition of nanoclay-based materials. It provides information on the thermal properties and behavior of nanoclay under different conditions (Peña-Parás et al., 2018).

Surface modification can be achieved by various methods, including acid treatment, surfactant treatment, and polymer grafting (Guo et al., 2018). Acid treatment involves the use of acid to remove impurities and increase the surface area of nanoclay. Surfactant treatment involves the use of surfactants to modify the surface chemistry and improve the dispersion of nanoclay in polymers. Polymer grafting involves the attachment of polymer chains to the surface of nanoclay, leading to improved compatibility with polymers (Guo et al., 2018). Surface chemistry modification of nanoclay is a crucial step in enhancing its compatibility with polymers. The most effective methods used to modify the surface chemistry of nanoclay are organic modification through ion-exchange reaction, surfactant-assisted modification, and aminopropylisooctyl polyhedral oligomeric silsesquioxane (POSS) modification. Organic modification through ion-exchange reaction is the conventional method of surface modification, where organic cations are incorporated into the clay structure through ion exchange with the inorganic cations present in the clay lattice (Chanra et al., 2019). The incorporation of organic cations offers hydrophobicity to the clay surface, making it compatible with polymers (Saikia, 2020). Surfactant-assisted modification method involves the use of surfactants that are capable of exchanging metal cations of the clay and are compatible with organic polymers (Zaferani, 2018). POSS modification is a new modification method that has shown promising results in enhancing the compatibility of nanoclay with polymers. In this method, the nanoclay surface is modified using Aminopropylisooctyl POSS, which increases the d-spacing of the clay and provides a hydrophobic environment to the galleries of the clay. This method has been successfully used in the synthesis of polycaprolactone (PCL)-clay Nanocomposites, resulting in enhanced thermal properties compared to pure PCL (Yusoh et al., 2018).

The surface chemistry modification of nanoclay affects its compatibility with polymers with enhancement of interfacial interactions, better dispersion of clay platelets, controlled polymerization, and tailor-made properties. Surface functionalization of nanoclays enhances the interfacial interactions between the nanoclay fillers and the polymeric matrix. This leads to improved mechanical, thermal, and barrier properties of the resulting polymer-nanoclay composites (Guo et al., 2018). It also helps in achieving a better dispersion of the clay platelets in the polymer matrix. This, in turn, improves the overall properties of the nanocomposites, such as increased tensile strength, modulus, and heat resistance (Guo et al., 2018). Moreover, surface-modified nanoclays can act as initiators or catalysts for polymerization reactions, leading to the *in-situ* synthesis of polymer-clay nanocomposites with improved properties (Guo et al., 2018). The choice of surface modification method and the type of organic cations used can be tailored to achieve specific properties in the resulting polymer-nanoclay composites, such as flame retardancy, electrical conductivity, and gas barrier properties (Guo et al., 2018).

III. Nanoclay Types

Nanoclays can be classified into different types based on their composition and structure. In this section, some of the most common types of Nanoclay are discussed.

Kaolinite group: This group includes kaolinite, zeolite, and halloysite nanoclays. They have a layered structure with a thickness of about 1 nm and a diameter of about 50-200 nm (Farzadnia and Shi, 2023; Kausar, 2020; Zaferani, 2018). The kaolinite group and the zeolite or halloysite group of nanoclays have some differences in terms of their composition and morphology. The kaolinite group includes minerals such as kaolinite and halloysite. Kaolinite has the chemical formula $Al_2Si_2O_5(OH)_4$ and typically occurs in platy forms. Halloysite, on the other hand, has a similar composition to kaolinite but contains additional water molecules between the layers and commonly has a tubular morphology (Hillier and Ryan, 2002). Kaolinite typically occurs in platy forms, while halloysite has a tubular morphology (Hillier and Ryan, 2002). Kaolinite is a very important industrial mineral, commonly used in various applications. Halloysite is also becoming increasingly important, especially in nanotechnology applications that take advantage of its tubular habit (Hillier and Ryan, 2002). The zeolite or halloysite group includes minerals such as zeolite and halloysite. Zeolite crystals have an interlocking texture similar to halloysite, contributing positively to the strength of materials. Halloysite has a tubular morphology and can exist in different forms, including hydrated and dehydrated states (Lampropoulou and Papoulis, 2021). The main difference between halloysite and kaolinite is the tubular morphology of halloysite. Zeolite crystals also have interlocking texture characteristics (Lampropoulou and Papoulis, 2021).

Montmorillonite group: This group includes montmorillonite nanoclay, which has a layered structure with a thickness of about 1 nm and a diameter of about 50-200 nm (Hossain et al., 2023; Yaghmaeiyan et al., 2022). Montmorillonite is composed of aluminum, silicon, oxygen, and other elements. Its structure consists of gibbsite surrounded by silica sheets on top and bottom and with van der Waals forces between the layers (Kumari and Mohan, 2021; Uddin, 2008). Montmorillonite has a high aspect ratio, high surface area, and good mechanical properties. It is also highly absorbent and can swell up to several times its original size when exposed to water (Uddin, 2008). Montmorillonite is used in various applications, including polymer nanocomposites, drilling fluids, and environmental remediation. It is also used in the production of high-performance cement nanocomposites, as it can improve the mechanical properties, durability, and fire resistance of cement-based materials (Hossain et al., 2023; Katti et al., 2022; Uddin, 2008; Yaghmaeiyan et al., 2022).

Mica group: Mica group is a type of clay mineral that is composed of potassium, aluminum, and silicon. It has a layered structure similar to other types of nanoclay, with a thickness of about 1 nm and a diameter of about 50-200 nm. Mica-type nanoclays are trioctahedral silicate clay minerals with a 2:1 layered structure similar to montmorillonite (Wang and Wang, 2019). It is used in various applications, including as fillers in polymer nanocomposites, as reinforcing agents in rubber, and as rheological modifiers in coatings and adhesives (Kumari and Mohan, 2021). Mica-type nanoclays have unique properties such as high surface area, and good mechanical properties, making them suitable for various applications.

Sepiolite group: This group includes sepiolite nanoclay, which has a fibrous structure with a diameter of about 20-50 nm and a length of about 1-10 microns. It is composed of magnesium, silicon, and oxygen (Hamid et al., 2021). It has a microfibrous morphology and a unique texture that provides a high specific surface area (Tian et al., 2019). Sepiolite is distinguished by its needle-like morphology and stratified layers resembling talc, which comprise two tetrahedral silica layers flanking a central octahedral magnesium layer, as reported by Biddeci et al. (2023). This mineral possesses a one-dimensional fibrous silicate clay structure with a 2:1 layer-chain arrangement, featuring two continuous tetrahedral sheets and one non-continuous octahedral sheet (Biddeci et al., 2023). Sepiolite exhibits numerous active surface groups and channels, rendering it amenable to diverse applications. Its fibrous structure and substantial surface area render it particularly suitable for health-related uses, such as drug delivery systems (Biddeci et al., 2023). Sepiolite is also utilized in the production of highly oriented nanocomposite tapes and as a flame retardant in polymer systems (Nguyen Thanh et al., 2023). The unique properties and structure of sepiolite make it a valuable material for different applications, particularly those that benefit from its fibrous morphology and high surface area.

Each type of nanoclay has its unique properties and characteristics, making them suitable for different applications. For example, montmorillonite nanoclay is commonly used in polymer nanocomposites due to its high surface area and good mechanical properties (Das et al., 2015) and halloysite nanoclay is used in drug delivery systems due to its high surface area and porosity (Kausar, 2020; Zaferani, 2018).

IV. Soil Stabilization

Soil stabilization is the process of modifying the physical, chemical, mechanical, biological, or combined properties of soil to improve its engineering properties. The goal is to increase the weight-bearing capacity, tensile strength, and overall performance of unstable subsoils, sands, and waste materials to strengthen road pavements and other construction projects. There are several methods of soil stabilization, including mechanical, compaction, chemical, and biological methods. Mechanical methods involve physically changing the properties of the soil, such as mixing and compacting two or more soils of different grades. Compaction methods involve applying pressure to the soil to increase its density and strength. Chemical methods involve adding additional material to the soil that will chemically and physically interact with it and change its properties, such as adding cement or chemicals to the soil. Biological methods involve afforestation or planting to control erosion and improve soil stability. The choice of soil stabilization method depends on the soil type, the engineering purpose, and the desired outcome (Afrin, 2017; Bordoloi et al., 2017; Celik and Nalbantoglu, 2013; Correia et al., 2016; Sharma and Sivapullaiah, 2016; Thom and Dawson, 2019; Vincevica-Gaile et al., 2021; Yadu and Tripathi, 2013; Zahri and Zainorabidin, 2019; Zuber et al., 2013). Fig. 3 shows the General soil stabilization methods.

A. The effectiveness of nanoclay compare to other soil stabilization methods

According to the available research, nanoclay has shown a promising way in improving the geotechnical properties of soils and enhancing soil stabilization. Here is a comparison of the effectiveness of nanoclay to other soil stabilization methods.

Advantages of Nanoclay

It was demonstrated that mixing 3% nanoclay with soft soil improved soil strength and effectiveness of shear strength (Khalid et al., 2015). Nanoclay can be used to stabilize soft soils and reduce their plasticity index, increase specific gravity, improve compaction, and enhance shear strength (Zhang, 2007). Nanoclay can be used as a reinforcing material in polymer composites, enhancing their strength, toughness, durability, and barrier properties (Arora et al., 2019).

B. Disadvantages of Nanoclay

Nanoclay is more expensive than traditional soil stabilizers, which can make it less cost-effective for some projects (Arora et al., 2019). Nanoclay may not be compatible with all types of soils or soil stabilizers (Zhang, 2007). The long-term durability of nanoclay-stabilized soils is not yet fully understood (Marjan Padidar et al., 2016).

SiO_2, TiO_2, and Al_2O_3 are other types of nanomaterials that can be used for soil stabilization (Arora et al., 2019). Fibers, polymers, industrial waste, and microbes are other materials that can be used for soil stabilization (Khodabandeh et al., 2023). The effectiveness of these methods may vary depending on the specific project and soil conditions.

C. The effectiveness of nanoclay according to the type of soil

According to extant research, the efficacy of nanoclay in soil stabilization appears to be contingent upon the soil type. A research investigation was conducted to assess the impact of nanoclay supplementation on the geotechnical characteristics of both clay and silt soils. The findings of this study demonstrated that the inclusion of nanoclay led to enhancements in soil strength and shear strength effectiveness, as reported by Khalkhali et al. (2019). A preliminary field investigation revealed that the incorporation of 2% nanoclay into loess soils resulted in a substantial enhancement of soil erosion control, as reported by Marjan Padidar et al. (2016). Additionally, a computational modeling study explored the influence of nanoclay on various soil parameters. The outcomes indicated that the introduction of nanoclay led to a moderate increase in the unconfined compressive strength and cohesion of the soil. Nevertheless, it is noteworthy that beyond a certain threshold, the effectiveness of nanoclay exhibited a diminishing trend, as elucidated by Kamgar et al. (2021). A study investigated the effect of adding nanoclay on some physical properties of sandy soil. The results showed that nanoclay improved the soil's water retention capacity and reduced its hydraulic conductivity (M Padidar et al., 2016).

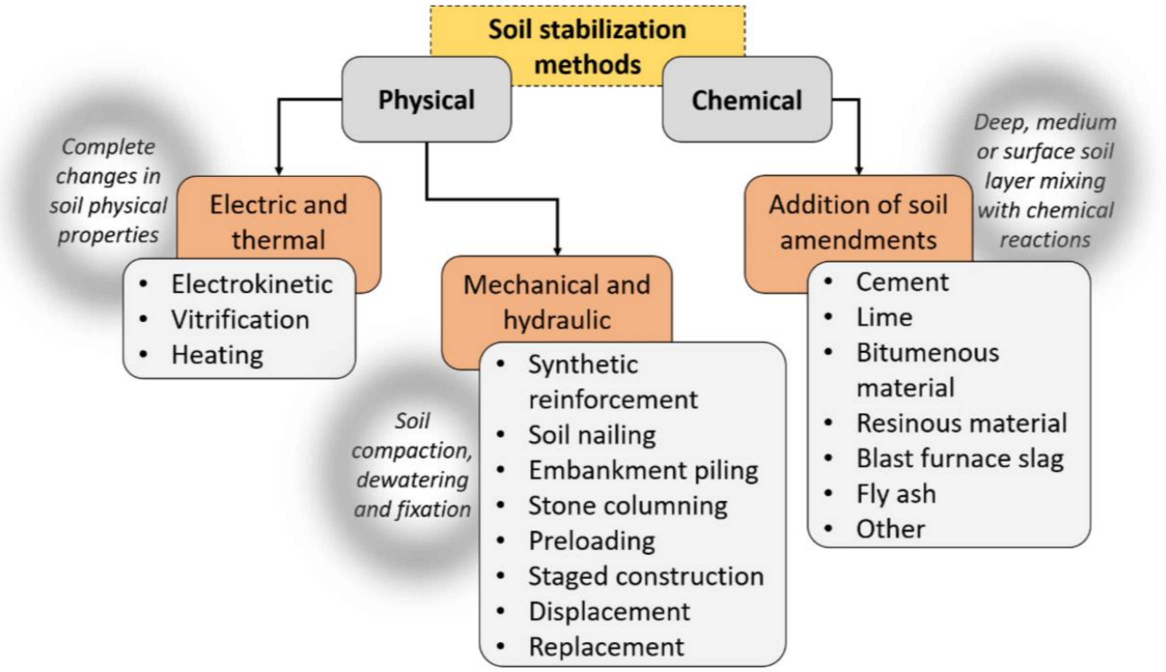

Fig. 3. General soil stabilization methods (Vincevica-Gaile et al., 2021)

Nanoclay can be used to stabilize different types of soil including:

1. Dispersive soils are soils that are prone to erosion and have poor geotechnical properties. Nanoclay can be added to dispersive soils to improve their strength and stability (Abbasi et al., 2018). It can be added to dispersive soils to improve their strength and stability. The addition of nanoclay can decrease the dispersivity of dispersive clayey soils, making them less prone to erosion and more stable (Abbasi et al., 2018; Majid et al., 2020). Nanoclay demonstrates the capability to mitigate the dispersive nature of soils by inducing flocculation among soil particles, thereby forming larger agglomerations. This process involves the penetration of the nanoclay within the soil structure, ultimately leading to the stabilization of the soil matrix (Guan and Zhao, 2020; Katschnig and Battisti, 2015). The addition of a low percentage of nanoclay to the soil can improve the level of dispersion, but adding excessive amounts may not be effective (Asakereh and Avazeh, 2017). Overall, the addition of nanoclay can be an effective method for stabilizing dispersive soils and improving their geotechnical properties.

2. Soft soils are soils that are prone to deformation and have low shear strength. Nanoclay can be added to soft soils to improve their strength and shear resistance (Khalid et al., 2015; Subramani and Sridevi, 2016). It can indeed be added to soft soils to improve their strength and shear resistance. Several studies have demonstrated the positive effects of nanoclay on soft soil stabilization. For example, the mixing of 3% nanoclay with soft soil has been shown to improve soil strength and the effectiveness of shear strength (Khalid et al., 2015). The addition of nanoclay to soft soil samples resulted in increased shear strength (Babu and Joseph, 2016). Adding nanoclay to cement soil improved its compressive and shear strength (Wang et al., 2022).

3. Clay and silt soil: Nanoclay can be added to clay and silt soils to improve their geotechnical properties, including reducing the plasticity index, increasing the specific gravity, improving compaction, and enhancing shear strength (Abbasi et al., 2018; Arora et al., 2019). It can be added to clay and silt soils to improve their geotechnical properties. The addition of nanoclay can reduce the plasticity index of clay and silt soils, making them less prone to deformation and more stable (Khalkhali et al., 2019). The addition of nanoclay can improve the compaction of clay and silt soils, making them more resistant to deformation and more stable (Arya and Jain, 2017; George and Kannan, 2020; Nikookar et al., 2013). Overall, the addition of nanoclay can improve the geotechnical properties of clay and silt soils, making them more stable and suitable for various engineering applications. The specific improvements may vary depending on the project and soil conditions. The addition of different nanomaterials, including nanoclay, to soft soil samples enhanced their properties (Subramani and Sridevi, 2016). Increasing the percentage of nanoclay in clay soil increased its unit weight, indicating improved compaction (Khalkhali et al., 2019). These findings suggest that nanoclay can effectively enhance the strength and shear resistance of soft soils, making them more stable and suitable for various engineering applications.

D. The effectiveness of nanoclay on the geotechnical properties

Nanoclay can improve the strength of soils by increasing cohesion and shear strength (George and Kannan, 2020; Kamgar et al., 2021; Niroumand et al., 2023; Subramani and Sridevi, 2016)(Kamgar et al., 2021). Overall, the addition of nanoclay can enhance the soil strength, making it more resistant to deformation and more stable. The specific increase in soil strength may vary depending on the project and soil conditions.

Nanoclay can reduce the plasticity index of soils, making them less prone to deformation and more stable (Karumanchi et al., 2020; Khalkhali et al., 2019; Maleki and Sharafi, 2014; Zoriyeh et al., 2020). The presence of nanoparticles in soil composition has been observed to correlate with an increase in both the liquid and plastic limits of the soil, as documented by Khalkhali et al. (2019). The increase in plasticity index may be useful in many applications (Maleki and Sharafi, 2014). Overall, the addition of nanoclay can increase the plasticity index of soil, making it less prone to deformation and more stable. The specific increase in plasticity index may vary depending on the project and soil conditions.

Nanoclay can increase the specific gravity of soils, making them denser and more stable (Subramani and Sridevi, 2016). A study investigated the effect of nanoclay additives on the geotechnical properties of clay and silt soil. The results showed that adding nanoclay increased the dry soil specific gravity (Khalkhali et al., 2019). Another study investigated the effect of adding nanoclay to natural soil. The results showed that the specific gravity of the soil increased after adding nanoclay (Karumanchi et al., 2020). So, the addition of nanoclay can increase the specific gravity of soil, making it denser and more stable. The specific increase in specific gravity may vary depending on the project and soil conditions.

Nanoclay can improve the compaction of soils, making them more resistant to deformation and more stable (Karumanchi et al., 2020). A study investigated the effect of nanoclay additives on the geotechnical properties of clay and silt soil. The results showed that by increasing the percentage of nanoclay, the unit weight of clay soil increased and the optimum moisture content decreased, indicating improved compaction (Khalkhali et al., 2019). An investigative modeling study was conducted to examine the impact of nanoclay on various soil parameters. The findings revealed that the incorporation of nanoclay led to a discernible enhancement in the unconfined compressive strength and cohesion of the soil, thereby potentially contributing to improved compaction, as elucidated by Kamgar et al. (2021). Another study investigated the effect of adding nanoclay to soft soil samples. The results showed that adding nanoclay improved the compaction of the soil, making it more resistant to deformation (Subramani and Sridevi, 2016). Accordingly, the addition of nanoclay can improve the compaction of soil and the specific improvement in compaction may vary depending on the project and soil conditions.

Moreover, nanoclay can reduce the permeability of soils, making them less prone to erosion and more stable (Karumanchi et al., 2020). According to the search results, the addition of nanoclay can reduce the permeability of soil. A study found that the permeability in soil samples reduced from 3.16×10^{-4} cm/s to 4.09×10^{-7}cm/s by increasing the nanoclay percentage up to 9% (Jafari and Abbasian, 2018). Another study investigated the effect of nanoclay additives on the geotechnical properties of clay and silt soil. The results showed that the addition of nanoclay reduced the permeability of the soil (Khalkhali et al., 2019). A modeling study investigated the effect of nanoclay on different parameters of soil. The results showed that adding nanoclay reduced the permeability of the soil (Kamgar et al., 2021). A study investigated the effect of nanoclay on some physical properties of sandy soil. The results showed that nanoclay reduced the hydraulic conductivity of the soil, which is an indicator of reduced permeability (M Padidar et al., 2016).

Finally, nanoclay can reduce the collapse potential of soils, making them more stable and less prone to subsidence (Arya and Jain, 2017). An investigation was undertaken to assess the effects of nanoclay on the collapse potential and geotechnical characteristics of gypseous soils. The findings revealed that the incorporation of 4% nanoclay into soil samples resulted in a significant 77% reduction in the collapse potential, as reported by Karkush et al. (2020). Another study investigated the effect of nanoclay additives on the geotechnical properties of clay and silt soil. The results showed that the addition of nanoclay improved the soil's strength and reduced its collapse potential (Zamanian and Qahremani, 2020). A modeling study investigated the effect of nanoclay on different parameters of soil. The results showed that adding nanoclay reduced the collapse potential of the soil (Kamgar et al., 2021).

E. Environmental impacts of using nanoclay for soil stabilization

Some chemical stabilizers may contain toxic materials that can harm the environment. Before selecting a chemical for soil stabilization, design engineers should consider environmental concerns, including toxicity and biodegradability (Jones, 2017). The techniques employed for soil stabilization may exhibit transient consequences, including heightened erosion and sedimentation rates, potential impacts on local ecosystems, and implications for human communities. Ground disturbance could also lead to the release of pollutants or contaminants (Makusa, 2013). Cement stabilization is a common method of soil stabilization that involves adding cement to the soil. However, the production of cement is a major source of greenhouse gas emissions, which can contribute to climate change. Mechanical soil stabilization involves altering the soil mechanically to lock it in place and prevent it from moving. This method can be beneficial for erosion control, but it may also involve the use of heavy machinery, which can disturb the soil and harm the environment (Corrigan and Black, 2020).

Based on the search results, there is limited information available specifically addressing environmental regulations or guidelines for the use of nanoclay in soil stabilization. However, it is important to note that the use of any material, including nanoclay, in soil stabilization should adhere to existing environmental regulations and guidelines that govern soil management and construction practices. These regulations and guidelines may vary depending on the country, region, or specific project.

In general, when using nanoclay or any other material for soil stabilization, it is recommended to consider the following environmental considerations:

1. Toxicity: ensure that the nanoclay formulation being used does not contain toxic materials that can harm the environment. It is important to use environmentally-friendly nanoclay formulations and follow proper disposal procedures for any waste materials (Abbasi et al., 2018).

2. Erosion and sediment control: implement erosion and sediment control measures to prevent the release of stabilized soil particles into nearby water bodies. This can include the use of erosion control blankets, sediment basins, or other best management practices (Constantinescu and Sicuia, 2020).

3. Environmental impact assessment: conduct an environmental impact assessment to evaluate the potential impacts of soil stabilization activities on the surrounding environment. This assessment can help identify and mitigate any potential risks or concerns (Arora et al., 2019).

4. Compliance with regulations: ensure compliance with local, regional, and national regulations governing

soil management, construction practices, and environmental protection. This may include obtaining necessary permits or approvals before undertaking soil stabilization activities (Subramani and Sridevi, 2016).

It is important to consult with local regulatory authorities, environmental experts, and soil stabilization specialists to ensure that the use of nanoclay or any other material for soil stabilization is in accordance with applicable environmental regulations and guidelines.

Some potential environmental impacts of using nanoclay for soil stabilization include soil contamination, erosion and sediment control, air pollution, and greenhouse gas emissions.

Nanoclay formulations may contain toxic materials that can contaminate the soil and harm the environment. It is important to use environmentally-friendly nanoclay formulations and to dispose of any waste materials properly (Marjan Padidar et al., 2016). Soil stabilization activities can increase erosion and sedimentation, which can impact nearby water bodies and ecosystems. Implementing erosion and sediment control measures can help prevent the release of stabilized soil particles into nearby water bodies (M Padidar et al., 2016). The use of nanoclay for soil stabilization can generate dust and particulate matter, which can contribute to air pollution. Proper dust control measures should be implemented to minimize the release of dust and particulate matter into the air (Marjan Padidar et al., 2016). The production of nanoclay can generate greenhouse gas emissions, which can contribute to climate change. It is important to use environmentally-friendly production methods and to minimize the carbon footprint of nanoclay production (Niroumand et al., 2023).

To mitigate these potential environmental impacts, it is recommended to use environmentally-friendly nanoclay formulations that do not contain toxic materials, implement erosion and sediment control measures to prevent the release of stabilized soil particles into nearby water bodies, use proper dust control measures to minimize the release of dust and particulate matter into the air, and use environmentally-friendly production methods and minimize the carbon footprint of nanoclay production.

V. Conclusion

Nanoclay is used in geostability to improve the properties of soils and enhance the performance of geotechnical materials. Its ability to swell and form stable gels, as well as its reinforcing properties, makes it a valuable component in geotechnical engineering applications.

Nanoclay holds promise as a soil stabilization agent in various industries and applications such as construction, agriculture, mining, and environmental remediation. However, its effectiveness and application can vary depending on factors such as soil type and project requirements. While nanoclay has shown potential in improving soil stabilization, there are challenges associated with its use that need careful consideration. The effectiveness of different soil stabilization methods can vary depending on project-specific factors and soil conditions, emphasizing the importance of thorough testing and expert consultation. The effectiveness of nanoclay for soil stabilization is influenced by the type of soil being treated. Conducting comprehensive testing and assessments is essential to identify the most suitable application of nanoclay for a specific soil type. Nanoclay can be used to stabilize various soil types, including dispersive soil, soft soil, clay, and silt soil. However, the effectiveness and application of nanoclay may differ based on the soil type and project requirements. Furthermore, it has the potential to improve various geotechnical properties of soils during soil stabilization, such as soil strength, plasticity index, specific gravity, compaction, permeability, and collapse potential. However, the specific improvements achieved will depend on the project and soil conditions. While soil stabilization methods can effectively enhance the geotechnical properties of soils, it is crucial to consider the environmental impacts associated with these methods. Whenever possible, environmentally-friendly soil stabilization methods should be employed, and thorough testing and environmental reviews should be conducted before implementing any soil stabilization approach.

In conclusion, it is imperative to consider the potential environmental impacts of using nanoclay for soil stabilization and take appropriate measures to mitigate these impacts. Proper waste management, ecotoxicological studies, monitoring of long-term stability, and sustainable production practices can help minimize the environmental risks associated with nanoclay use.

Acknowledgments

Sedighi acknowledges the support of Cellular and Molecular Research Center, Birjand University of Medical Sciences, Birjand, Iran.

Conflicts of Interest

The authors declare no conflict of interest.

References

Abbasi, N., Farjad, A., Sepehri, S. (2018). The use of nanoclay particles for stabilization of dispersive clayey soils. Geotech. Geol. Eng. 36, 327–335.

Abulyazied, D.E., Ene, A. (2021). An investigative study on the progress of nanoclay-reinforced polymers: Preparation, properties, and applications: A review. Polymers (Basel). 13, 4401.

Afrin, H. (2017). A review on different types soil stabilization techniques. Int. J. Transp. Eng. Technol. 3, 19–24.
Albdiry, M.T., Yousif, B.F., Ku, H., Lau, K.T. (2013). A critical review on the manufacturing processes in relation to the properties of nanoclay/polymer composites. J. Compos. Mater. 47, 1093–1115.
Arora, A., Singh, B., Kaur, P. (2019). Performance of Nano-particles in stabilization of soil: a comprehensive review. Mater. Today Proc. 17, 124–130.
Arya, A., Jain, A. (2017). A review of geotechnical characteristics of nano-additives treated soils. Int J Adv Res Sci Eng 6, pp. 838–843.
Asakereh, A., Avazeh, A., 2017. The Effect of Nano Clay on Dispersive Soil Behavior (Case Study of Minab City). Amirkabir J. Civ. Eng. 49, 503–512.
Azzam, E.M.S., Sayyah, S.M., Taha, A.S. (2013). Fabrication and characterization of nanoclay composites using synthesized polymeric thiol surfactants assembled on gold nanoparticles. Egypt. J. Pet. 22, 493–499.
Babu, S., Joseph, S. (2016). Effect of nano materials on properties of soft soil. Int J Sci Res 5, 634–637.
Biddeci, G., Spinelli, G., Colomba, P., Di Blasi, F. (2023). Halloysite Nanotubes and Sepiolite for Health Applications. Int. J. Mol. Sci. 24, 4801.
Bordoloi, S., Sekharan, S., Garg, A. (2017). A review of physio-biochemical properties of natural fibers and their application in soil reinforcement. Adv. Civ. Eng. Mater. 6, 323–359.
Celik, E., Nalbantoglu, Z. (2013). Effects of ground granulated blastfurnace slag (GGBS) on the swelling properties of lime-stabilized sulfate-bearing soils. Eng. Geol. 163, 20–25.
Constantinescu, F., Sicuia, O.A.B. (2020). Phytonanotechnology and plant protection, in: Phytonanotechnology. Elsevier, 245–287.
Correia, A.G., Winter, M.G., Puppala, A.J. (2016). A review of sustainable approaches in transport infrastructure geotechnics. Transp. Geotech. 7, 21–28.
Corrigan, B., Black, N. (2020). Vegetation Management Plan 81-91 Railway Terrace Schofields, NSW.
Das, P., Malho, J.-M., Rahimi, K., Schacher, F.H., Wang, B., Demco, D.E., Walther, A. (2015). Nacre-mimetics with synthetic nanoclays up to ultrahigh aspect ratios. Nat. Commun. 6, 5967.
Di Ianni, E., Møller, P., Mortensen, A., Szarek, J., Clausen, P.A., Saber, A.T., Vogel, U., Jacobsen, N.R. (2020). Organomodified nanoclays induce less inflammation, acute phase response, and genotoxicity than pristine nanoclays in mice lungs. Nanotoxicology 14, 869–892.
Farzadnia, N., Shi, C. (2023). Use of nanomaterials in geopolymers, in: Nanotechnology for Civil Infrastructure. Elsevier, 161–190.
George, A., Kannan, K. (2020). Investigation on the geotechnical properties of nano clay treated clayey soil. Int J Res Eng Sci Manag 3, 453–455.
Guan, H., Zhao, Y. (2020). Decontamination application of nanoclays, in: Clay Nanoparticles. Elsevier, 203–224.
Guo, F., Aryana, S., Han, Y., Jiao, Y. (2018). A review of the synthesis and applications of polymer–nanoclay composites. Appl. Sci. 8, pp. 1696.
Hamid, Y., Tang, L., Hussain, B., Usman, M., Liu, L., Ulhassan, Z., He, Z., Yang, X. (2021). Sepiolite clay: A review of its applications to immobilize toxic metals in contaminated soils and its implications in soil–plant system. Environ. Technol. Innov. 23, 101598.
Hayles, J., Johnson, L., Worthley, C., Losic, D. (2017). Nanopesticides: a review of current research and perspectives. New Pestic. soil sensors, 193–225.
Hillier, S., Ryan, P.C. (2002). Identification of halloysite (7 Å) by ethylene glycol solvation: the 'MacEwan effect.' Clay Miner. 37, 487–496.
Hossain, S.I., Kukushkina, E.A., Izzi, M., Sportelli, M.C., Picca, R.A., Ditaranto, N., Cioffi, N. (2023). A review on montmorillonite-based nanoantimicrobials: state of the art. Nanomaterials 13, 848.
Jafari, B., Abbasian, K. (2018). Experimental study of the nanoclays effects on soil permeability reduction to preparing Landfill liners vs leachate. Geotech. Geol. 14, 217–221.
Jagadeesh, P., Puttegowda, M., Thyavihalli Girijappa, Y.G., Rangappa, S.M., Siengchin, S. (2022). Effect of natural filler materials on fiber reinforced hybrid polymer composites: An Overview. J. Nat. Fibers 19, 4132–4147.
Jones, D., 2017. Guidelines for the selection, specification, and application of chemical dust control and stabilization treatments on unpaved roads.
Kamgar, R., Salimi Naghani, M., Heidarzadeh, H., Nasiri Ardali, F. (2021). Modeling nanoclay effects on different parameters of a clayey sand. Model. Earth Syst. Environ. 7, 795–808.
Karkush, M.O., Al-Murshedi, A.D., Karim, H.H. (2020). Investigation of the Impacts of Nano-clay on the Collapse Potential and Geotechnical Properties of Gypseous Soils. Jordan J. Civ. Eng. 14.
Karumanchi, M., Avula, G., Pangi, R., Sirigiri, S. (2020). Improvement of consistency limits, specific gravities, and permeability characteristics of soft soil with nanomaterial: Nanoclay. Mater. Today Proc. 33, 232–238.
Katschnig, M., Battisti, M. (2015). Processing of polymer–nanoclay composites, in: Polymer Nanoclay Composites. Elsevier, 53–91.
Katti, K.S., Jasuja, H., Jaswandkar, S., Mohanty, S., Katti, D.R. (2022). Nanoclays in medicine: a new frontier of an ancient medical practice. Mater. Adv. 3(20), 7484-7500.
Kausar, A., 2020. Flame retardant potential of clay nanoparticles, in: Clay Nanoparticles. Elsevier, pp. 169–184.
Kausar, A., Ahmad, I., Maaza, M., Eisa, M.H. (2022). State-of-the-Art Nanoclay Reinforcement in Green Polymeric Nanocomposite: From Design to New Opportunities. Minerals 12, 1495.
Khalid, N., Mukri, M., Kamarudin, F., Abdul Ghani, A.H., Arshad, M.F., Sidek, N., Ahmad Jalani, A.Z., Bilong, B. (2015). Effect of nanoclay in soft soil stabilization, in: InCIEC 2014: Proceedings of the International Civil and Infrastructure Engineering Conference 2014. Springer, 905–914.
Khalkhali, A.B., Safarzadeh, I., Manbar, H.R. (2019). Investigating the effect of nanoclay additives on the geotechnical properties of clay and silt soil. J Mater Civ. Eng 3, 63–74.
Khodabandeh, M.A., Nagy, G., Török, Á. (2023). Stabilization of collapsible soils with nanomaterials, fibers, polymers, industrial waste, and microbes: Current trends. Constr. Build. Mater. 368, 130463.
Kumari, N., Mohan, C. (2021). Basics of clay minerals and their characteristic properties. Clay Clay Min. 24, 1–29.
Lampropoulou, P., Papoulis, D. (2021). Halloysite in different ceramic products: A review. Materials (Basel). 14, 5501.
Majid, M.S.A., Ridzuan, M.J.M., Lim, K.H. (2020). Effect of nanoclay filler on mechanical and morphological properties of napier/epoxy composites, in: Interfaces in Particle and Fibre Reinforced Composites. Elsevier, 137–162.
Makusa, G.P., 2013. Soil stabilization methods and materials in engineering practice: State of the art review.
Maleki, Y.S., Sharafi, H. (2014). The exploration into the effect of nanoclay additive on soil geotechnical-engineering basic properties. Adv. Environ. Biol. 989–993.
Mašín, D., Khalili, N. (2015). Swelling phenomena and effective stress in compacted expansive clays. Can. Geotech. J. 53, 134–147.
Mattausch, H. (2015). Properties and applications of nanoclay composites, in: Polymer Nanoclay Composites. Elsevier, 127–155.
Nazir, M.S., Mohamad Kassim, M.H., Mohapatra, L., Gilani, M.A., Raza, M.R., Majeed, K. (2016). Characteristic properties of nanoclays and characterization of nanoparticulates and nanocomposites. Nanoclay Reinf. Polym. Compos. Nanocomposites bionanocomposites, 35–55.
Nguyen Thanh, T.T., Szolnoki, B., Vadas, D., Nacsa, M., Marosi, G., Bocz, K. (2023). Effect of clay minerals on the flame retardancy of polylactic acid/ammonium polyphosphate system. J. Therm. Anal. Calorim. 148, 293–304.
Nikookar, M., Bahari, M., Nikookar, H., Arabani, M. (2013). The strength characteristics of silty soil stabilized using nano-clay, in: Proceedings of 7th Symposium on Advances in Science & Technology 7thSASTech, Bandar-Abbas, Iran. 1–7.

Niroumand, H., Balachowski, L., Parviz, R. (2023). Nano soil improvement technique using cement. Sci. Rep. 13, 10724.
Osman, A.F., Fitri, T.F.M., Rakibuddin, M., Hashim, F., Johari, S.A.T.T., Ananthakrishnan, R., Ramli, R. (2017). Pre-dispersed organo-montmorillonite (organo-MMT) nanofiller: Morphology, cytocompatibility and impact on flexibility, toughness and biostability of biomedical ethyl vinyl acetate (EVA) copolymer. Mater. Sci. Eng. C 74, 194–206.
Padidar, M, Jalalian, A., Abdouss, M., Najafi, P., Honarjoo, N., Fallahzade, J. (2016). Effects of nanoclay on some physical properties of sandy soil and wind erosion. Int. J. Soil Sci. 11, 9–13.
Padidar, Marjan, Jalalian, A., Asgari, K., Abdouss, M., Najafi, P., Honarjoo, N., Fallahzade, J. (2016). The impacts of nanoclay on sandy soil stability and atmospheric dust control. Agric. Conspec. Sci. 81, 193–196.
Peña-Parás, L., Sánchez-Fernández, J.A., Vidaltamayo, R. (2018). Nanoclays for biomedical applications. Handb. Ecomater. 5, 3453–3471.
Perera, K.Y., Hopkins, M., Jaiswal, A.K., Jaiswal, S. (2023). Nanoclays-containing bio-based packaging materials: Properties, applications, safety, and regulatory issues. J. Nanostructure Chem. 1–23.
Shahidi, M., Asemi, F., Farrokhi, F. (2023). Improving the mechanical behavior of soil contaminated with Gas–Oil using organoclay and nanoclay. Arab. J. Sci. Eng. 48, 4953–4969.
Shakrani, S.A., Ayob, A., Rahim, M.A.A. (2017). A review of nanoclay applications in the pervious concrete pavement, in: AIP Conference Proceedings. AIP Publishing.
Sharma, A.K., Sivapullaiah, P.V. (2016). Ground granulated blast furnace slag amended fly ash as an expansive soil stabilizer. Soils Found. 56, 205–212.
Shunmugasamy, V.C., Xiang, C., Gupta, N. (2015). Clay/polymer nanocomposites: processing, properties, and applications. Hybrid hierarchical Compos. Mater. 161–200.
Subramani, V., Sridevi, S. (2016). Soil stabilization using nano materials. Int J Res Appl Sci Eng Technol 4, 641–645.
Thom, N., Dawson, A. (2019). Sustainable road design: Promoting recycling and non-conventional materials. Sustainability 11, 6106.
Tian, G., Han, G., Wang, F., Liang, J. (2019). Sepiolite nanomaterials: structure, properties and functional applications, in: Nanomaterials from Clay Minerals. Elsevier, 135–201.
Uddin, F. (2008). Clays, nanoclays, and montmorillonite minerals. Metall. Mater. Trans. A 39, 2804–2814.
Vincevica-Gaile, Z., Teppand, T., Kriipsalu, M., Krievans, M., Jani, Y., Klavins, M., Hendroko Setyobudi, R., Grinfelde, I., Rudovica, V., Tamm, T. (2021). Towards sustainable soil stabilization in peatlands: Secondary raw materials as an alternative. Sustainability 13, 6726.
Wang, W., Wang, A. (2019). Nanoscale clay minerals for functional ecomaterials: Fabrication, applications, and future trends. Handb. Ecomater. 2019, 2409–2490.
Wang, Y., Wang, W., Zhao, Y., Li, N., Luo, J., Belete, A.M., Ping, J. (2022). Modification Effect of Nano-Clay on Mechanical Behavior of Composite Geomaterials: Cement, Nano-Silica and Coastal Soft Soil. Materials (Basel). 15, 8735.
Yadu, L., Tripathi, R.K. (2013). Effects of granulated blast furnace slag in the engineering behaviour of stabilized soft soil. Procedia Eng. 51, 125–131.
Yaghmaeiyan, N., Mirzaei, M., Delghavi, R. (2022). Montmorillonite clay: Introduction and evaluation of its applications in different organic syntheses as catalyst: a review. Results Chem. 100549.
You, Z., Mills-Beale, J., Foley, J.M., Roy, S., Odegard, G.M., Dai, Q., Goh, S.W. (2011). Nanoclay-modified asphalt materials: Preparation and characterization. Constr. Build. Mater. 25, 1072–1078.
Yu, Q.L. (2019). Application of nanomaterials in alkali-activated materials, in: Nanotechnology in Eco-Efficient Construction. Elsevier, 97–121.
Zaferani, S.H. (2018). Introduction of polymer-based nanocomposites, in: Polymer-Based Nanocomposites for Energy and Environmental Applications. Elsevier, 1–25.
Zahri, A.M., Zainorabidin, A. (2019). An overview of traditional and non traditional stabilizer for soft soil, in: IOP Conference Series: Materials Science and Engineering. IOP Publishing, 12015.
Zamanian, M., Qahremani, F. (2020). Investigating the effect of Portland cement and Nano-clay on the collapse potential and consolidation indexes of the collapsible soil. Amirkabir J. Civ. Eng. 52, 1439–1454.
Zhang, G. (2007). Soil nanoparticles and their influence on engineering properties of soils, in: Advances in Measurement and Modeling of Soil Behavior. 1–13.
Zoriyeh, H., Erdem, S., Gürbüz, E., Bozbey, İ. (2020). Nano-clay modified high plasticity soil as a building material: Micro-structure linked engineering properties and 3D digital crack analysis. J. Build. Eng. 27, 101005.
Zuber, S.Z.S., Kamarudin, H., Abdullah, M., Binhussain, M. (2013). Review on soil stabilization techniques. Aust. J. Basic Appl. Sci. 7, 258–265.