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Stabilization Expansive Clayey with Nano-Lime to Reduce Environmental Impact

Ali Akbar Firoozi[a]*, Maryam Naji[b] & Ali Asghar Firoozi[c]

[a]*Department of Civil Engineering, Faculty of Engineering & Technology, University of Botswana*
[b]*Department of Civil Engineering, Higher Education Complex of Saravan, Saravan, Iran*
[c]*Department of Civil Engineering, Faculty of Engineering, Universiti Kebangsaan Malaysia (UKM), Malaysia*

Corresponding author: a.firoozi@gmail.com

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ABSTRACT

For years, geotechnical engineers have been concerned about expansive soils. Expansive soils are characterized by large volumetric changes related to variations in moisture content. Variations in soil water content may take place naturally during seasonal changes or maybe manmade caused by dewatering activities. The quantity of shrinkage and swell is influenced by numerous parameters, including the quantity of minerals clay in the soil, moisture content, dry density, and climate change. In most countries, numerous structures, including pavements and buildings, are damaged as a result of this shrinkage/swelling. Several ground improvement techniques are available for stabilizing expansive soil to modify its engineering performance. These methods include soil replacement, mixing with chemical additives, and soil reinforcement. The present study expressions the effect of nano-lime (i.e., 0.1, 0.3, 0.5, 0.7, 1.0, 2.0 and 3.0%), and lime (1, 3, 5, 8, and 10%), as chemical additive to improve clayey soil (i.e., illite and kaolinite). The effect of nano-lime and lime were investigated using Atterberg's limits tests. The Atterberg limits were screening significant changes in the proportion of additional nano-lime and lime. The results show that less amount of nano-lime (1% and 2% for illite and kaolinite respectively) decreased the plastic limit, while for lime it was reported 8% for illite and 5% for kaolinite respectively. In conclusion, less quantity of nano-lime (1-2%) is able to improve soil parameters.

Keywords: Nano-lime; lime; illite; kaolinite; chemical stabilization

INTRODUCTION

The application of nanotechnology in various fields is receiving widespread attention. Nanotechnology is the process of re-engineering materials and devices at the atomic level. In other words, nanotechnology is a field driven by advances in basic chemistry and physics research, in which atomic and molecular understanding is applied to create materials and structures that perform tasks that are not achievable using the materials in their classic macroscopic form (Firoozi et al. 2014; Alsharef et al. 2016; Mobasser et al. 2016; Firoozi et al. 2014).

The use of additives is beneficial since cost-effectiveness is one of the most significant requirements for civil engineering projects. Land that has to be improved can sometimes cover a wide area and span long distances. As a result, the necessity to keep the project on budget necessitates the use of low-cost materials. Industrial by-products or garbage have also been widely explored to meet this requirement and these highlighted an essential question (Firoozi et al. 2017). Hazardous chemical leaching into the environment has caused health problems, hence another key condition for candidate materials for soil improvement is that they must not leach toxic chemicals into the environment. An easily interpretable plasticity chart, on the other hand, is provided for using the Atterberg limits of clays as a tool for identifying them and researching their physical properties. Because the required equipment is simple and inexpensive, this deterministic technique has obvious appeal for under-equipped laboratories and even temporary field stations. The chart was created primarily for geologists working in developing nations, where the main interest in clay minerals is their potential for commercial exploitation, and the emphasis is on recognizing industrial clay types (Chittoori et al. 2013; Taha et al. 2013; Kazemian 2010; Chittoori, 2003).

Improvement of an extremely highly plastic expansive clay with hydrated lime and fly ash studied by Süt Ünver et al. (2021). They mixed clayey with additional 1, 3, 5, 7, and 9% of lime and 5%, 10%, 15, 20, and 25% of fly ash. They showed that lime content reducing the liquid limit and plasticity index ranged from 4 to 5%, whereas approximately 8% lime was necessary to attain an allowable swell percentage, whereas, fly ash did not effectively improve the extremely highly plastic clay in reasonable amounts (20 to 25%) in terms of its swelling properties. Sudhakar et al. (2021) studied performance of quarry dust treated expansive clay for road foundations. They added the quarry dust (10-25%) to clay samples. They found that the unconfined compressive strength (UCS) as well as the maximum dry density increases up to 85% soil + 15% quarry dust proportion. Hence, the swell potential decreases from 14.73 to 7.17% at 15% of quarry dust.

Improving engineering characteristics of expansive soils using industry waste as a sustainable application for reuse of bagasse ash is investigated by Dang et al. (2021). Their results revealed that addition of bagasse ash (BA), lime, and in particular, combined BA-lime remarkably improved the maximum strength (815%), the bearing capacity (9.2 times), the compressibility (83%), and the 100% swell properties of stabilized soils due to rich amorphous silica properties of BA waste that promoted higher pozzolanic reactivities of BA-lime-soil-mixtures and therefore, enhanced the engineering characteristics of treated soils. Also, they showed that a proper combination of BA waste and lime, as a stabilizing additive, can effectively enhance the engineering properties of expansive soil while addressing the environmental impact of BA waste disposal. Zha et al. (2021) considered engineering properties of expansive soil stabilized by physically amended titanium gypsum. They found that the coarse particles of the soil increased and the plasticity index, swelling potential shrinkage, and compression index decreased while the strength characteristics of unconfined compressive strength, cohesion and internal friction angle of the stabilized soil were significantly improved. They recommended 7 days curing time for stabilizing the expansive soil. Also, stabilized soil at 25% titanium gypsum admixture can satisfy the requirements of the Chinese standard for subgrades below Grade II.

Improvement of engineering properties of expansive soil using liming leather waste ash examined by Parihar & Gupta (2021). They observed that the liming leather waste ash contains cementitious characteristics of lime and silica combined and can substantially reduce the plasticity and swell-shrink behavior of the soil and improve its strength and bearing characteristics. The UCS and California bearing ratio (CBR) values have also shown multifold increase post curing with UCS and soaked CBR escalating by 278% and 387% respectively.

Pachideh et al. (2021) evaluated the rate of engineering properties of expansive soils caused by the effect of varying curing temperature together with the addition of silica nanoparticles on lime. Based on the results, as the temperature decreases (especially temperatures below 20 ^{o}C with storage duration shorter than 28 days), pozzolanic activities as well as growth process of cementitious mixtures (e.g., CSH and CAH nanostructures), was disrupted and after the addition of lime, the improvement process will be majorly affected by short-term reactions (cation exchange capacity and increase in Osmotic pressure). Conclusively, application of lime-silica nanoparticles (especially in cold weather and short curing duration) intensifies the lime's effect and in addition, reduces the consumption of additives by 50%.

Elhakim et al. (2022) examined improvement of expansive soil using granulated scrap tires. Treated soil samples are mixed with different amounts of granulated scrap tires (5, 10, and 15% by weight of soil). The effects of mixing different percentages of either cement or lime (0 to 6% by soil weight) to the soil-granulated scrap tires mixture are also investigated. The test program included the index properties, maximum dry density/optimum moisture content, California bearing ratio, swelling potential, and unconfined compressive strength tests. They recommended the use of granulated scrap tires on the behavior of the tested swelling clay. Assessment of swelling and strength characteristics of expansive soil with addition of waste recycled product (WRP) studied by Choudhary et al. (2021). Their test results revealed that addition of WRP to expansive soil in appropriate proportion not only reduces its swelling and shrinkage behaviour but also there is a significant improvement in its strength and deformation characteristics. After adding 30% WRP (by dry weight of soil) in expansive soil, the percentage increase in subgrade modulus and unconfined compressive strength was 89.18% and 68.78%, respectively.

Fernandez et al. (2021) investigated performance of calcium lignosulfonate (CLS) as a stabilizer of highly expansive clay. CLS is a bio-based polymer, obtained as a sub-product of the paper industry. Clay was stabilized using 3.0 and 5.0% mass of CLS. The efficiency of CLS as a stabilizing agent was measured studying its influence on the physical properties of Clay (Atterberg limits, Cation Exchange Capacity, Specific Surface Area). Considerable reductions of the cation exchange capacity and the specific surface were registered. They showed that a relatively small amount of CLS might yield a reasonably satisfactory performance as a stabilizer, particularly in reducing the natural Clay's swelling potential. Moreover, CLS induced an increase in the stiffness and strain at failure of Clay and a reduction in its porosity.

The effect of zeolite and cement stabilization on the mechanical behavior of expansive soils examined by Chenarboni et al. (2021). They used four different cement contents (6, 8, 10, and 12%) and various percentages of cement replacement with zeolite (0, 10, 30, 50, 70, and 90%). They found that the addition of cement led to an increase in the maximum dry density and optimum moisture content of the soil-cement mixture, whereas increasing the zeolite content resulted in opposite trends. After 28 days of the curing period, cement replacement with 30% zeolite also resulted in achieving the maximum UCS. The maximum UCS improvement rate was obtained from 12% cement replaced with 30% zeolite in the specimen.

Limestone is broken down at high temperatures to form lime (i.e., over 900 ^{o}C). As a result, three forms of lime are produced: hydrated lime (calcium hydroxide–), quicklime (calcium oxide – CaO), and hydrated lime slurry; all of which can be used to treat soils.

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Calcium carbonate (limestone–) is chemically transformed into calcium oxide to make quicklime. In addition, when quicklime reacts chemically with water, hydrated lime is formed. Strong cementitious connections are produced when hydrated lime and clay particles are joined. Lime has been demonstrated to reduce the swelling potential, liquid limit, plasticity index, and maximum dry density of soils while increasing the optimum water content. It also improves the workability and compact ability of subgrade soils. When lime is given to clayey soil, it causes the soil to become more alkaline. Depending on the type of clay being treated, these treatments can take a long time to complete. As a result, the lime-treated soil is allowed to cure for 1 to 4 days, as mellowing aids in the formation of a consistent or homogeneous mixture (Al-Rawas et al. 2005; Ismail, 2014). When lime is combined with water and the soluble silica and alumina in the clay, a chemical reaction occurs, resulting in the formation of new compounds. When coupled with water, its primary function is to alter particle structure and increase resistance to shrink-swell and moisture susceptibility. Particle binding and strength gain are secondary effects when clay is mixed with it. To obtain a homogenous, friable combination, a mellowing period of 1 to 4 days is recommended, because particle structure changes slowly depending on the type of clay employed. The following is a summary of these reactions:

$$Ca^{++} + OH^{-} + \text{Soluble Clay Silica} \rightarrow \text{Calcium Silicate Hydrate (CSH)} \quad (1)$$

$$Ca^{++} + OH^{-} + \text{Soluble Clay Alumina} \rightarrow \text{Calcium Alumina Hydrate (CAH)} \quad (2)$$

Lime stabilization enhances soil engineering attributes such strength, resistance to fracture, fatigue, and permanent deformation, enhanced resilient properties, reduced swelling, and moisture-related damage resistance. The clays with moderate to high plasticity show the greatest improvements in these properties (Firoozi et al. 2017).

According to Al-Kiki et al. (2011) the properties of treated soil have an impact on strength increase over time. Soil pH, organic content, exchangeable sodium, clay mineralogy, natural drainage, weathering conditions, extractable iron, carbonates, and the silica-alumina ratio are some of the elements that influence strength increase. When lime was used to stabilize acidic soil, the compressive strength was lower than in alkaline soil (Ghobadi et al. 2014; Abdullah & Abdullah, 2013).

Finally, the goal of this study is to introduce nano-lime to use for civil engineering projects rather than traditional lime and show how with the use of very less amount of nano-lime (i.e., 1-2%) we will take the same results when using a higher proportion of lime (i.e., 5-8%) and with this method reduce the environmental effect. Plastic limit and liquid limit were two of the characteristics investigated in this study.

EXPERIMENTAL SETUP

Kaolinite and illite were the clay minerals and silica sand with fine-grained particles (45 microns) used in this research. Clayey samples (i.e., kaolinite and illite) were obtained in commercial packages to control the quality of the tests (Fig. 1). Kaolinite, illite, and silica was dried at 100 ± 5 ^{o}C for over 24 hours in the laboratory oven (ASTM D2216 - 19). Properties of kaolinite, illite, nano-lime and hydrated lime are shown in Tables 1 to 4, which were obtained by conducting a series of geotechnical laboratory tests by using ASTM standards. Also, the arrangement and shapes of particles (kaolinite, illite, and nano-lime) are displayed in Figs. 2 to 4 which are captured by scanning electron microscope (SEM).

FIGURE 1. A typical commercial packs of kaolinite (S-300) and Illite (KM800)

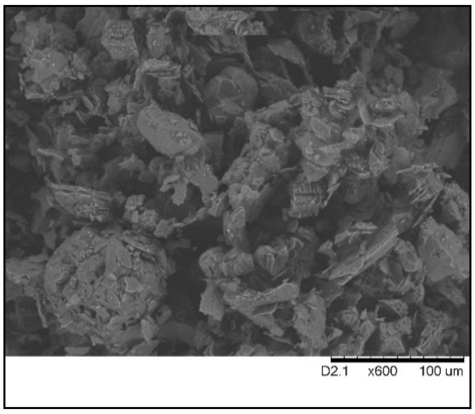

FIGURE 2. Kaolinite elements under SEM

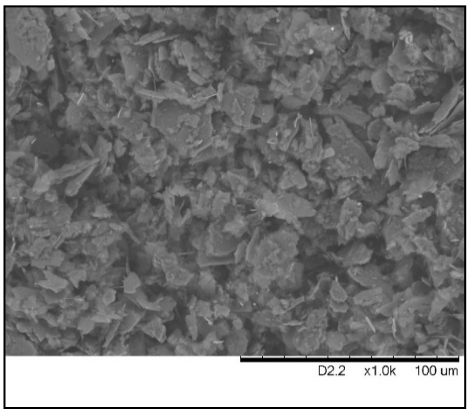

FIGURE 3. Illite elements under SEM

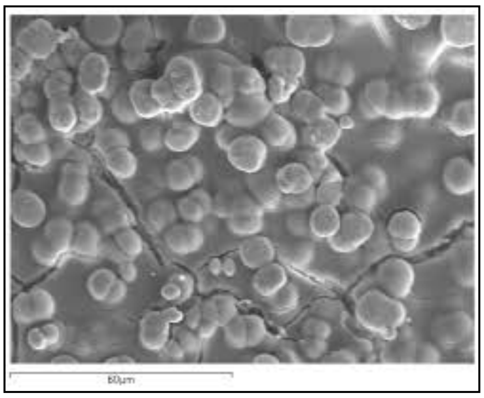

FIGURE 4.
NANO-LIME elements under SEM

TABLE 1. Material's properties of clayey

Illite		Kaolinite	
Specific gravity (Gs) ASTM D854	2.701	Specific gravity (Gs) ASTM D854	2.723
pH	4.5	pH	4.0
Moisture content	Below 2.0%	Moisture content	Below 1.5%
Average particle size	2.5-5.0µ	60 mesh residue	Below 0.5%
325 mesh residue	Below 3.0%	100 mesh residue	Below 10%

TABLE 2. Chemical compositions of materials

Silica Sand		Kaolinite		Illite	
Formula	Concentration (%)	Formula	Concentration (%)	Formula	Concentration (%)
Al_2O_3	2.71	Fe_2O_3	0.38	TiO_2	1.36
SiO_2	97.29	K_2O	1.34	MgO	1.76
-	-	Al_2O_3	9.11	Fe_2O_3	1.85
-	-	SiO_2	85.76	K_2O	8.21
-	-	heat loss	3.41	SiO_2	29.43
-	-	-	-	Al_2O_3	52.37
-	-	-	-	heat loss	5.02

TABLE 3. Chemical composition and surface area of nano-lime

Formula	Concentration (%)
SSA (specific surface area) m^2/g	93
CaO	78.00
Fe_2O_3	10.90
Al_2O_3	8.50
SiO_2	3.00

TABLE 4. Chemical contents of hydrated lime

Formula	Concentration (%)
$Cao\ (OH)_2$	90.0
MgO	3.0
$CaCO_3$	6.0
As	11 p.p.m
Pb	8 p.p.m
SSA (specific surface area) m^2/g	48

SOIL MIXTURES

Mixing nano-sized powders (i.e., nano-lime) with macro-sized particles (soil) is a key concern. Thus, in this research, the horizontal ball mill method was used for the mingling of soil through nano-lime (Firoozi et al. 2019). Mixing of the powders was performed at a laboratory scale. Forces created during mixing should be calculated to determine the viability of a nanoparticle mixing method. The degree of these forces is then determined to be larger than the adhesive or cohesive forces acting on powders. Mechanical forces are electrostatic and magnetic attraction, Van der Waals, and chemical forces are divided into two classes: first, forces that do not require physical bonds, such as, electrostatic, magnetic attraction, and Van der Waals forces. Second, forces that do require material bridges, such as liquid bonds and capillary attachment forces. In general, the first group is more important at low humidity, whereas the second progresses at moisture condition. As a result, molecular forces govern the adhesive and cohesive forces that act among elements in dry particle mixing, and their relevance reduces as particle size increases.

Interparticle forces are minimal in contrast to particle weight for relatively large elements (greater than 20 mm). These forces can be ignored in mixing, and the efficacy of a dry mingling procedure can be measured in terms of the applied macroscopic forces. These powders could be blended precisely, as long as the applied macroscopic forces, such as shear and compressive or extensional stresses, are significant enough to break any loosely shaped aggregates. In the most conditions, mixing can be accomplished by simply shaking the powder, with the mixing efficiency being the only consideration. The overall motion of particles must be appropriate for efficient mixing and can be measured in terms of particle paths' spatial distribution.

The filling ratio and media ratio (Eqs. 3 & 4) were calculated in the first part of the inquiry to optimize the mixing process, and the kinetics of mixing was evaluated in the second part. The dried soil was then divided into two stages and blended with nano-lime. Pre-mixing or manual mixing took place for 20 minutes before the sample was placed into a 1.5 L plastic container. The mixture was then milled for one to 24 hours with steel balls (i.e., 5,8, and 12 mm) (Figs. 5 & 6).

$$\text{Filling Ratio (FR)} = \frac{V_{\text{feed}}}{V_{\text{chamber}}} = \frac{V_{nano-lim\,e} + V_{soil} + V_{balls}}{V_{chamber}} \tag{3}$$

$$\text{Media Ratio (MR)} = \frac{V_{nano-lim\,e} + V_{soil}}{V_{nano-lim\,e} + V_{soil} + V_{balls}} \tag{4}$$

The intensity and size of segregation were used to assess mixing quality with absorption data collected from X-ray diffraction (XRD) and energy-dispersive X-ray spectroscopy (EDX) investigations. The corresponding de-agglomeration was computed using particle size analysis which used Malvern Mastersizer 2000. Also, field-emission scanning electron microscopy (FESEM), and specific surface was capture to check the effects of particle size distribution. After six (6) hours of horizontal milling at 4 to 1 ratio of balls to the soil mix, FESEM examination revealed that nano-lime had an acceptable distribution. However, after 6 hours of ball milling, the ratio of agglomeration of nano-lime powder was reduced.

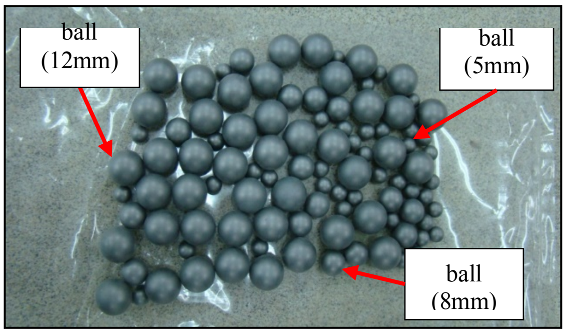

FIGURE 5. Planetary steel ball mills (5,8,12 mm)

FIGURE 6. Horizontal ball mill process was used in this study

50 per cent clay (kaolinite/illite) + 50 per cent silica sand was chosen for the test. The proportions of nano-lime chosen were (0, 0.1, 0.3, 0.5, 0.7, 1, 2, and 3% respectively) reactively of the total dry weight of the soil mixture and selected lime were (0, 1, 3,5, 8, and 10% respectively). Finally, according to the ASTM D4318-17 standard, the plastic limit (P.L.) and liquid limit (L.L.) tests were performed.

RESULT AND DISCUSSION

The effects of nano-lime and hydrated lime content on the liquid limit (L.L.) and plasticity index (P.I.) soil mixtures are shown in Figs. 7 to 10. For both illite and kaolinite mixtures, the L.L. increased as the percentage of nano-lime and lime differed. The reason for that is nano-lime and lime absorb water to process chemical reactions between self and clay particles. However, water absorption was more for illite mixtures with the addition of nano-lime and lime percentages due to the more cation exchange between illite particles. While the curve of P.L. decreased to a minimum for illite mixture when the percentage of nano-lime reached 2%, and for kaolinite mixtures, the minimum P.L. index happens when nano-lime touched to 1%. For lime, the P.L. significant decreased by 8% and 5% for the illite and kaolinite mixture respectively. The high surface area of nano-lime and the unique properties of this nanomaterial are the causes of this behavior between nano-lime and lime. As a result, adding small amounts (nanomaterials) to the soil can improve its qualities even at modest doses.

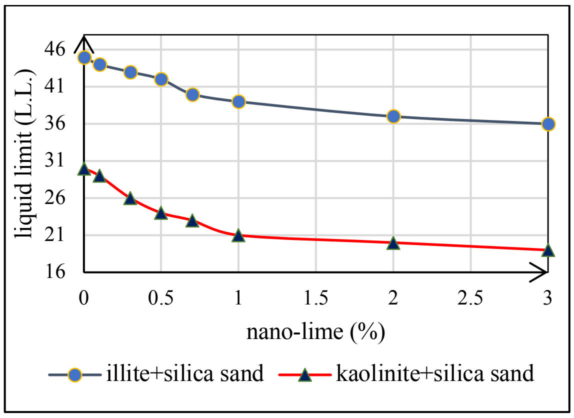

FIGURE 7. Effects of nano-lime on the L.L.

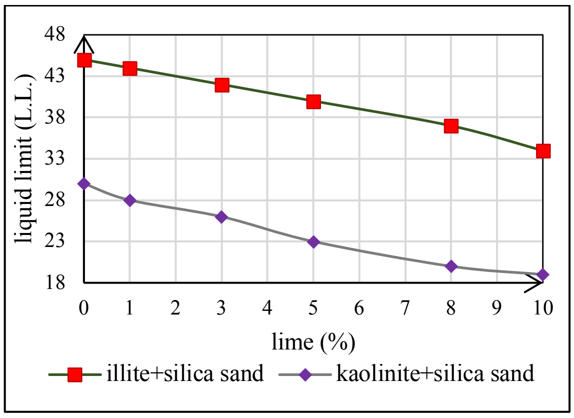

FIGURE 8. Effects of lime on the L.L.

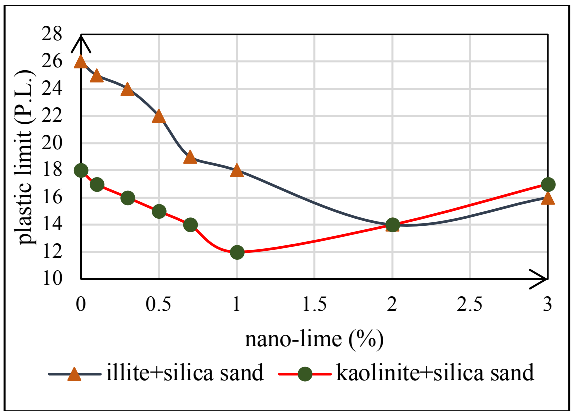

FIGURE 9. Effects of nano-lime on the P.L.

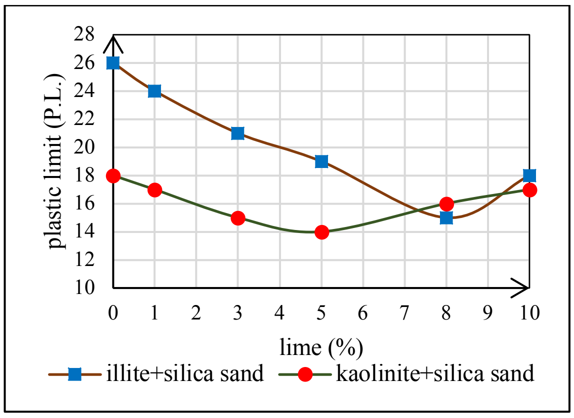

FIGURE 10. Effects of lime on the P.L.

CONCLUSION

Hazardous chemical leaching (i.e., lime, cement, and fly ash) into the environment has caused health problems, hence another key condition for candidate materials for soil improvement is that they must not leach toxic chemicals into the environment. To meet the sustainable aspect demanded by modern infrastructures, civil engineering projects are increasingly turning to the usage of environmentally friendly materials. As a result, in the last two decades, the expansion of this concept, combined with rising global warming, has prompted concerns about the widespread use of Portland cement, fly ash, and lime, owing to the substantial carbon dioxide emissions associated with their manufacture and it is needed to reduce amount this kind of materials. The development of nanotechnology and nanomaterials concretes point to a shift in soil stabilizing techniques and other civil engineering projects. This study revealed that using nano-lime and hydrated lime as an additive to improve expansive clayey parameters (i.e., plastic limit). The results show that a few of amount nano-lime (1-2%) can significantly decrease the P.L. of clayey do high surface area and unique properties of nano-lime compare the same results that found with hydrated lime (5-8%). As it is clear the average amounts of used nano-lime was six times less. Finally, the present study has been done on commercial mineral clayey and it is need to do more examine on natural clayey with different percentages and recommend more comprehensive research on different regions as well as on montmorillonite minerals.

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DECLARATION OF COMPETING INTEREST

None.

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