Environment, Development and Sustainability (2024) 26:13831–13894
https://doi.org/10.1007/s10668-023-03277-y

REVIEW

A critical appraisal on some geotechnical properties of soil stabilised with nano-additives

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Received: 25 August 2022 / Accepted: 18 April 2023 / Published online: 27 April 2023

Abstract

Soft clays are susceptible to uneven settlement due to its higher tendency of swelling and shrinkage which could damage the structures. To prevent such damages various soil stabilisation techniques have been used. Now day's many researchers have entered in geotechnical field to modify the geotechnical properties of problematic soils with nano-additives. Nanomaterials such as nano-silica, nano-clay, nano-lime, nano-carbons etc. were utilised in past studies to adjust geotechnical properties of problematic soils. In this review article, the impact of nano-additives on Atterberg's limit, compaction, consolidation, permeability, swelling and shrinkage of soil reported by various researchers is presented. An increment in dry unit weight and decrement in optimum moisture content of low plasticity soils was seen with incorporation of nano-additives whereas, vice versa effect was displayed with fine grained soil. The lower dosage of nano-additives provided equivalent consistency limits as compared to higher dosage of conventional additives. Up to certain amount, the incorporation of nano-additives led to reduction in consolidation parameter, permeability, swelling, and shrinkage of soil. From the detailed review of literature, it can be concluded that it is advantageous to incorporate nano-additives to improve the geotechnical properties of problematic soils.

Keywords Problematic soils · Nano-additives · Atterberg limits · Compaction · Consolidation · Permeability · Swelling and shrinkage

List of symbols

W_l	Liquid limit
W_p	Plastic limit
PI	Plasticity index
W_s	Shrinkage index
$\gamma_{dmax.}$	Maximum dry unit weight
ω_{opt}	Optimum moisture content

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Cc	Compression index
Cv	Coefficient of consolidation
Cr	Recompression index
mv	Volume compressibility
Cp	Collapse potential
C–S–H	Calcium silicate hydrate
C–A–H	Calcium aluminate hydrate
FSI	Free swell index
CNF	Carbon nano-fibres
CNT	Carbon nano-tubes
CL	Low compressible soil
CH	High compressible soil
CI	Intermediate compressible soil
SM	Silty sand
Kv	Coefficient of permeability

1 Introduction

Soils existing under the structure such as commercial or residential should be able to take the load without any settlement and shear failure in short as well as long term. Weak soils are highly are susceptible to failures due to settlement and shear. Soft clay such as bentonite is composed of montmorillonite mineral which has higher tendency of swelling and shrinkage and could damage the structure. Various remedies have been implemented to adjust the geotechnical properties of weak and soft soils as per field requirement such as mechanical stabilisation, chemical stabilisation, biological stabilisation etc. Traditional stabilisers such as cement have intense effect on environment pollution as it is manufactured by coal. It led to the emission of harmful gases such as carbon dioxide, Sulphur dioxide and Nitrous dioxide after utilising heavy amount of energy, water and aggregate material which represents cement as unsustainable additive Van Oss and Padovani (2003). The other issue with the cement grouting is the penetrability of the grout. Cement grout has higher viscosity and bigger particle size in suspension which required higher pressure during injection in finer soil. This led to cost increment with higher disturbance to the surroundings. The particle size of the nano-additives is at the nano-scale which could penetrate inside the pores of the finer soil and thus eliminates the requirement of higher pressure infusion which reduces the disturbance to the already constructed surroundings and also became cost effective. The traditional chemical additives such as sodium silicate, epoxy, acrylate and polymer solvents may offer a significant risk of waterway pollution (Vik et al., 2000). These kind of chemical solutions has non-aqueous nature and mostly soluble in organic solvents which are expensive. The usage of polymer-based solvents in grouting present higher risk of explosion due to their toxic and inflammable nature. Oppositely the available nano-materials such as Colloidal silica, nano-silica, nano-clay, nano-alumina, nano-carbons (CNTs), nano-magnesia, nano-alumina, nano-lime are based on silicon dioxide, alumina, carbon, magnesium and calcium respectively which are non-toxic and inert (Lam et al., 2006; Mauter & Elimelech, 2008). Such nanomaterials deliver higher price/performance ratio, non-toxicity and are eco-friendly (Huang & Wang, 2016). They act as a sustainable soil stabilisers by reducing the consumption of pozzolanic materials such as cement which directly influences the carbon footprints and reduces the pollution (Choobbasti et al., 2019).

The majority of the nano-additives such as nano-silica, nano-carbons, nano-alumina and nano-clay mentioned in the study are environment-friendly except some additives which are metal based as they could raise problem due their toxicity nature such as nano-copper, nano-titanium oxide. These nano-additives could raise issues of lung inflammation during the application period and are not cost effective (Grassian et al., 2007). Nano-additives such as nano-silica, nano-alumina and nano-magnesia are based on silicon dioxide, aluminium oxide and magnesium oxide which are also found in soil composition.

The stabilisation of soil with nano-additives has been emerging out from past few years and reported to be a better modifier of physical, chemical and microstructural properties of soil than traditional additives such as lime and cement according to the requirement in relevant geotechnical application area. Nanoparticles shows higher level of reactivity at nano- and micro-scale level due to their higher specific surface area which enable them to react properly with the soil particles as compared to traditional stabilisers such as lime and cement in a more uniform and homogeneous way. Coarse grained soils (loose sands) nearby coastal areas are highly susceptible to liquefaction failures in which large uneven settlement of soil can be observed and has the capability to do large destruction of building situated nearby such places. Collapsible soils such as loess are also problematic due to their higher tendency of volume reduction. The mitigation of such soils has been carried out with the help of nano-stabilisation by various researchers.

Nano-technology is defined as the manipulation of matter on atomic and molecular scale. In 1959, Richard fynman in his talk "there is plenty of room at the bottom" seeded the concept of nano-technology. K Eric Dexler in 1986 used the term nano-technology in his book inspired by concept of fynman's known as "Engines of creation: the coming era of Nanotechnology". National Nanotechnology initiative defined nano-technology as manipulation of matter in 1–100 nm sized dimension (Huang & Wang, 2016). The compression of grain size distribution of nano is shown in Fig. 1. Nano-structures can be divided into four categories based on dimension size as shown in Fig. 2 (Krishnan & Shukla, 2019):

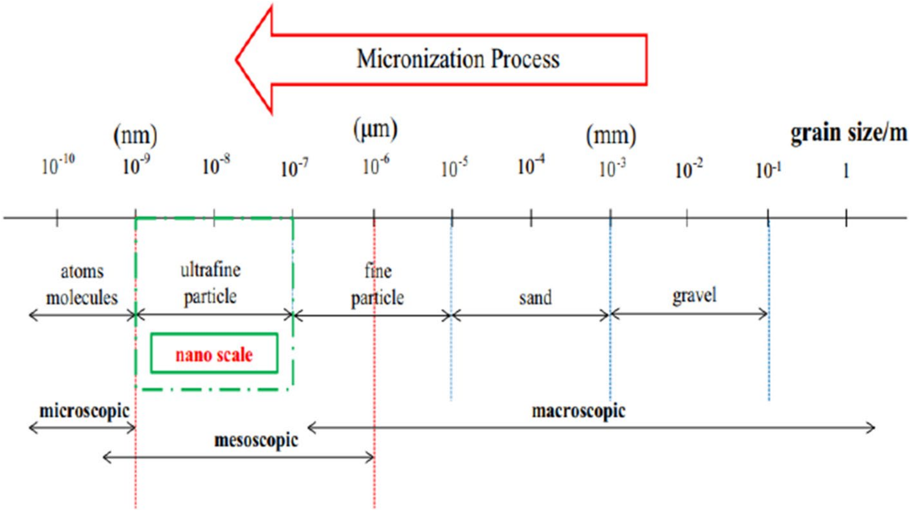


Fig. 1 Comparison of grain size distribution (Huang & Wang, 2016)

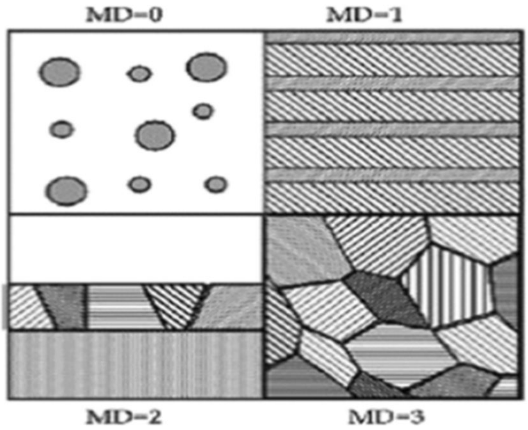


Fig. 2 Nanostructures (Krishnan & Shukla, 2019)

- Zero dimensional: All the three dimensions are confined to the nano-scale level. Example. Nanoparticles, colloidal particles etc.
- One dimensional: Two dimensions are confined to the nano-scale and any one dimension is outside the nano-level. Example. Nano-tubes, nano-rods, nano-wires etc.
- Two dimensional: Any single dimension was confined to the nano-scale and remaining other two is not confined. Example. Discs, platelets etc.
- Three dimensional: All the three dimensions are not restricted to the nano-scale level. Example. Dispersion of nanoparticles, bundle of nano-wires etc.

Nanotechnology has been widely used in field of medicals, electronics, fuel cells etc. From few past year's researchers are working on utilisation of nano-additive in the field of civil engineering works as well. Nanoparticles such as nano-silica, nano-clay, nano-lime, nano-carbons, nano-copper, nano-alumina, nano-MgO has been broadly used in concrete and soil stabilisation. Nano-silica was used both in powdered as well as colloidal form. Nano-silica powder was found useful to improve strength and durability purposes in weak clays where colloidal form was found effective in the reduction of liquefaction intensities in loose sands (Krishnan et al., 2021). Collapse potential of collapsible soils (Loess) was transformed from severely collapsible to slightly collapsible nature with the help of nano-clay and nano-silica additives (Haeri & Valishzadeh, 2020). Nano-carbons such as carbon nano-tubes (CNTs) and carbon nano-fibres (CNFs) reduced the swelling and shrinkage tendencies of highly plastic clays contained montmorrilonite mineral and thus found beneficial in crack mitigation (Taha et al., 2018). Nano-clay effectively reduced the hydraulic conductivity of soil by clogging of pores due to its smaller particle size and improved the performance of clay liners (Salemi et al., 2016).

In some studies, Nanoparticles were simultaneously admixed with cemented compounds such as lime and cement (Kulanthaivel et al., 2020). Nano-additives enhanced the reactivity of cementitious compounds by providing uniform and homogeneous dispersion due to higher specific surface area. The higher specific surface area had provided better interfacial contact area of cementitious compounds with soil particles and improved the properties at nano- and micro-scale level. Further, nanoparticles formed additional cementitious compounds which improved the inter particle bonding and provide stiffer and denser soil matrix with less plasticity (Changizi & Haddad, 2015). The reduced plasticity indicated lesser volume change and decreased the tendency of swelling and shrinkage. This regulation of soil with respect to swelling and shrinkage helped to maintain soil subgrade properties for pavements.

Some studies incorporated fibres along with nano-additives and reported improved interlocking and adhesiveness of the fibres with the soil particles and resist the deformation (Tomar et al., 2019). The fibres along with nanoparticles helped in the reduction of crack intensities and found beneficial in application as lining for solid waste disposal. Nano-stabilised soil had satisfied the criteria for prevention of seepage related practical issues in lining of canal, core of earthen dam, tunnels and structures of underground etc. Other nano-additives such as in the form of Polymers (polypropylene homopolymers) of nano-scale was studied by Azzam (2014) and observed formation of nano-composites after reaction with the soil particles and reduced the plasticity characteristics. Nano-chemicals such as terrasil was previously studied by Singh (2017) which helped in the reduction of swelling tendency due to increased dry density of highly compressible clay.

This review articles aims to summarise the most relevant investigation carried out by various research on the soil stabilised with nano-additives. This paper is limited to summarise the effect of nano-additives on geotechnical properties of soil such as Atterberg's limits, compaction, consolidation, and permeability, swelling and shrinkage. Further, the mechanism of soil interaction with different nanoparticles has been also documented.

2 Review of literature

2.1 Atterberg's limit

This section of the paper presented the influence of various types of nano-additives such as nano-silica, nano-lime, nano-clay, nano-carbon fibres etc. on the consistency limits of expansive clayey soils, Silty sandy soils, collapsible and liquefied sands. Consistency limits such as W_l, W_p, W_s, PI and linear shrinkage indicates the plasticity characteristics or firmness of soil structure with change in water content. The impact of traditional additives such as lime and cement on plasticity characteristics of soils were compared to the nano-treated soils. Simultaneous treatment of nano-additives with cement and lime was also inspected to achieve maximum improvement in the geotechnical properties. At the end, adequate concluded remarks are stated on the basis of changed Atterberg's indices after treatment with the nano-additives.

2.1.1 Nano-silica- and nano-silane-based compounds

Ugwu et al. (2013) documented the influence of organo silane-based nano-compound on silty sand and laterite soil with the dilution ratio of 1:300, 1:200 and 1:150. The treated soils showed reduction in W_l, W_p and PI. The reduction in PI was attributed to the hydrophobic behaviour of treated soils caused due to formation of siloxane bonds at the molecular level. The reaction of nano-compound with the silicates present in the soil formed stronger siloxane bond. The negative charge of the clay particles was neutralised by siloxane bonds which reduced the absorbed water layer and decreased the plasticity. The reaction of geopolymer based on fly ash (Shekhawat et al., 2022) with the soil particles was also similar with the organo silane-based nano-compound. The reaction mechanism of nano-silica- and organo-silane-based nano-compound involves the formation of long chain of stronger siloxane bonds (Si–O–Si) from the Silanol bonds (Si–O) during hydrolysis. Bahmani et al. (2014) studied clayey soil stabilised with nano-silica with different particle sizes (80 nm and 15 nm) along with the cement. Dosages of nano-silica and cement were varied from 0.2–1 to 2– 8%, respectively. The lowest PI of clayey soil was observed at 0.2% nano-silica content with 4% and 6% cement content. Nano-dosage above optimum recorded increment in plasticity. The lower W_p was noticed with 15 nm sized additive as compared to 80 nm at 4% and 6% cement content. But 8% cement dosage reported higher W_p with 15 nm than 80 nm sized additive. Kirithika et al. (2015) compared the plasticity characteristics of nano-treated and non-nano-treated clay. Soil was incorporated with 5% nano-silica with 10% nano-lime and resulted higher W_l, W_p and PI than non-nano-sized silica and lime at similar dosages. Higher specific surface area of the nano-additives accommodated more water and resulted in higher plasticity. Moharram et al. (2016) performed consistency analysis on nano-silica and nano-kaoline amended clayey soil with nano-content of 0.5–2% by wt. of soil for both additives. W_l and W_p was increased as the composition of nanoparticles raised in soil matrix. Higher rate of increment in W_p than W_l which reduced the PI of the soil. Nanoparticles possess higher area to volume ratio and activity which increased the water absorption. Ghasabkolaei et al. (2016) experienced increment in W_l and W_p which reduced the PI of clay after incorporation of cement. Further treatment of cemented clay with nano-silica (1–3%) increased the W_l but no change was noticed in W_p and caused increment in the PI. The lowered PI with cement was due to ion exchange reactions of cement with the clay after hydration. The increase in plasticity by nano-silica was attributed to its higher specific surface area and active reaction with the cemented clay. Hanson et al. (2016) investigated consistency behaviour of CL, CH and bentonite treated with nano-silica (0.1–1%) and nano-silver (1%). The reduction in W_l, W_p and PI was reported and was proportional to the dosage. The maximum reduction was observed at 1% nano-content and nano-silica was more effective than nano-silver due to higher dissolution in nano-silica-treated samples. $\mathrm{W_l}$ showed decrement of 7%, 6% and 19% for CL, CH and bentonite respectively at 1% nano-silica content.

Kulkarni and Mandal (2017) incorporated fly ash (10–50%) and nano-material (organo silane based) in silty clay with the dilution ratio of 1:600, 1:400, 1:225, 1:100. The reduction in W_l, W_p and PI was observed after treatment with additives. Fly ash alone reduced the W_l and W_p by 1.69 times and 1.65 times respectively at 30% dosage and beyond that less prominent change was recorded. The mutual addition of fly ash with nano-material reduced the indices consistently. W_l and W_p experienced maximum decrement of 1.67 and 1.89 times than natural soil at 30% Fly ash with nano-material concentration of 1:100. The additives modified the medium compressible nature of soil to low compressible. The reaction of nano-chemical with the silica formed siloxane bonds by destruction of silanol groups during hydrolysis. These siloxane bonds imparted hydrophobicity to the soil particles. The negative charge found on the gain surface was neutralised by siloxane bonds and reduced the plasticity. Changizi and Haddad (2017) modified the consistency limits of soft clay with nano-silica particles with the variation in dosage of 0.5%, 0.7% and 1% by wt. of soil. The treated soil observed reduction in W_l and increment in W_p which caused to the declination of PI. W_s was also decreased in proportion to the nano-silica content. The maximum reduction in W_l was 11.5% at 0.7% dosage as compared to neat soil beyond that less significant reduction was noticed. So, the optimum dosage was considered to be 0.7%. The reduction in plasticity at optimum nano-content (0.7%) was reported as 52%. Nano-additive enhanced the interlocking force between soil particles which decreased the W_s. The viscous gel produced due to reaction between additive and soil imparted better bonding than adsorbed water. The reduction in inter particle spacing had increased the interfacial contact surface area and improved the frictional resistance. García et al. (2017) recorded minimal increment in the W_l and W_p after amendment of lacustrine highly compressible clay with nano-silica (0.5–3%). The water absorbed by nano-silica might be the reason for raised consistency limits. Eswaramoorthi et al. (2017) compared the impact of non-nano-sized and nano-sized silica and lime particles on the Atterberg's indices of the clay. The additives were incorporated with 5% nano-silica and 10% lime for both nano- and non-nano-sized particles. W_l was reduced and increment in W_p was reported which resulted in the decrement of PI with both sized additives. The clay treated with nano-sized particles recorded higher plasticity than non-nano-sized particles. Nano-additives possessed higher specific surface area which resulted increase in water holding capacity and thus experienced more plasticity.

Shaker (2018) assessed the impact of nano-silica on consistency of clayey soil. A significant increment in W_l and slight increase in W_p was noticed which produced increment in the PI. Nisha and Roy (2018) amended plastic clay with nano-silica (5–30%) and sodium bentonite (10–35%). The increment in Atterberg's limits was attributed to the higher rate of water absorption due to increased specific surface area of the particles. Malik et al. (2019) observed increment in W_l and W_p of clayey soil (MH) after treatment with nano-silica (5–20%). These indices were found to be proportionally increased up to 15% nano-dosage beyond that decrement was noticed. Also slight decrement in the plasticity index due to change in the consistency limits was noticed. Ahmadi and Shafiee (2019) examined the consistency of clayey soil after incorporation of nano- and micro-silica as admixtures. Micro silica slightly reduced the W_l and PI due to exchange of cations. Clay treated with nano-silica reported no tangible changes up to 1% dosage where significant increment in the W_l, W_p and PI was experienced above 2% dosage. The increase in consistency limits were attributed to the higher specific surface area of admixture which led to higher water requirement in hydration process. Kalhor et al. (2019) determined the impact of nano-silica on the consistency limits of fine-grained clayey soil. The treated soil experienced increase in W_l and W_p but observed reduction in PI proportionally with the dosage of nano-silica (1–4%) as shown in Fig. 3. The trend of increment in W_p was higher than W_l and thus reduced the PI of the soil. Higher specific surface area and energy of nano-silica caused higher water absorption. The reduction in plasticity was attributed to the change in

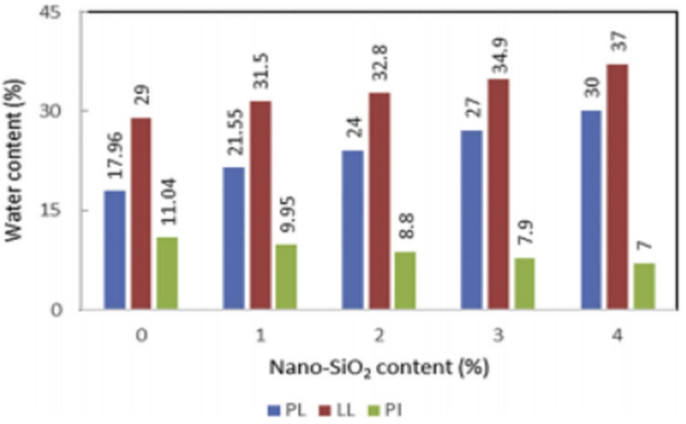


Fig. 3 Consistency limits of nano-silica-treated clay (Kalhor et al., 2019)

moisture absorption. Parsakhoo (2019) examined the influence of nano-silica and horse tail ash on the consistency behaviour of CH and CL. Four Mixtures of nano-silica and ash was prepared as 0.5% + 1%, 1% + 2%, 1.5% + 3%, 2% + 4% and denoted as mixture no. 1, 2, 3 and 4 respectively. In case of CH, both W_l and W_p showed consistent raise as the dosage increases where PI was reduced. In case of CL, increment in W_l and W_p was reported up to mixture 2 and then reduced. Plasticity index of CH experienced fluctuation and minimised at mixture 2. Higher specific surface area of the nano-silica produced more hydrated cations which generated thicker double water layer and increased the Atterberg's limit.

Sobhani Nezhad et al. (2020) modified the gas oil contaminated clay with nano-silica and hydrated lime after incorporation with dosages as 1%, 2% and 3% by weight of soil for both individual and simultaneous (1:1) treatment. The treated soil showed increment in both W_l and W_p where reduction in PI was recorded as the additives content in the soil increases. The reduction in PI indicates higher workability of soil. Gas soil also alone increased the W_l and W_p due to restriction in formation of double diffuse layer which caused higher requirement of water to stay in plastic nature. Higher specific surface area of nano-silica provided higher water absorption sites. Whereas hydrated lime formed cementitious compounds which possessed higher water absorption capability and ultimately caused higher consistency limits. The mixture of nano-silica and hydrated lime required more water to satisfy the cation exchange reactions due to higher pozzolanic nature of additives. The trapped water between the micro and nano-void spaces also caused higher limits of consistency. Ghavami et al. (2021) demonstrated the impact of nano-silica (0.5–2%) and silica fume (5–20%) on cement kiln dust (CKD) (15%)-treated clay. Nano-silica proportionally increased the W_l with the dosage where the W_p was initially increased and then reduced on higher dosages. Increment in PI was also reported in nano-silica-treated CKD clay. Higher packing density and higher surface energy was provided by tiny nano-silica particles which was responsible for reduced W_p. The increment in PI was attributed to higher specific surface area. Silica fume reduced the W_l, W_p and PI of the CKD soil due to cation exchange capacity and replacement of low plastic material with the clay. Kalhor et al. (2022) documented increment in W_l and W_p of clay after addition of nano-silica powder. PI of the treated clay was reduced due to higher incremental rate of W_p than W_l.

2.1.2 Nano-copper, nano-alumina and nano-magnesium oxide

Majeed and Taha (2012) used nano-CuO, nano-MgO and nano-clay as additives with soft soil (OL) of penang. Soil was incorporated with nano-clay and nano-MgO with dosages as 0.1%,-0.4% by dry wt. of soil for both, whereas nano-CuO was added as 0.5–1% by wt. of soil. The W_l, W_p and PI of stabilised soil reduced after treatment with all the three additives individually. Low dosages of nano-materials displayed slight changes in the soil behaviour. Luo et al. (2012) treated cohesive soil with combination of SSA (sewage sludge ash) and Cement with replacement of 15% proportion in raw clay and observed reduction in W_l and PI due to pozzolanic activities of SSA involved in hydration process. The treated soil was further treated by nano-alumina (1–3%) and reported higher reduction in plasticity index due to improved pozzolanic performance of SSA and cement. The effective results were obtained at 1% optimum dosage of nano-alumina. Taha and Taha (2012) studied four different types of clay soils by varying the content of bentonite in soil as 0%, 5%, 10% and 20% and named as S1, S2, S3 and S4, respectively. Nano-clay was used only for S1 while nano-alumina and nano-copper was used for all types for soil samples. Nano-clay increased the PI of S1due to its high expansive nature. Nano-alumina and nano-copper reduced the

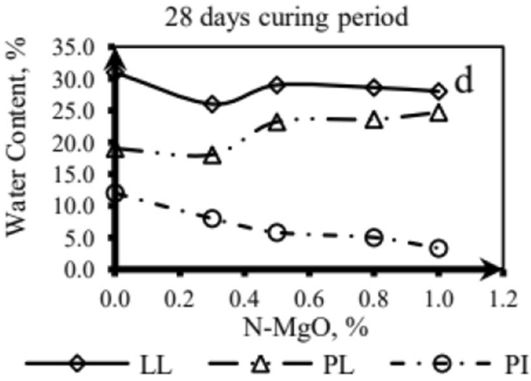
PI of the soil (all types) due to their high density of particles than clay. Nano-Cu showed significant reduction in PI as compared to nano-alumina due to its higher particle density. Nano-copper and nano-alumina has higher particle density than the soil particles which increased the density of the soil matrix and reduced the plasticity. The better modification credit is provided by nano-copper than nano-alumina due to its higher particle density. The improved bonding characteristics between particles enhanced the performance of soft soil due to attraction of negative surface charges of soil particles by the positive surface charges of these additives at the time of ion exchange process. Similarly, Siddiki and Singh (2020) reported decrement in W_l, W_p and PI in kaolinite clay after incorporation it with nano-alumina. Nano-alumina filled the pores between the particles and restricted the entry of the water and thus responsible for reduction in consistency limits.

Taha et al. (2015) compared the influence of regular (R-MgO) and nano-magnesium oxide (N-MgO) on the consistency of clay. Both the additives reduced the W_l and increased the W_p but in different trend. The amendment in the consistency limits reduced the PI which was in proportion to the curing period and dosage. R-MgO showed continuous decrement in W_l where N-MgO reduced it up to 0.3% dosage and then slight increment was experienced which was still less than the original soil as shown in Fig. 4. The reduction in PI was more prominent with N-MgO compared to R-MgO. Coo et al. (2016) conducted water displacement method to evaluate the W_s of nano-CuO and nano-Al_2O_3-treated clayey soil and recorded increment of about 17% and 8% in shrinkage limit respectively at 6% dosage. The increment in W_s indicated lesser volume reduction in soil mass. Kirithika and Stalin (2019) studied the influence of nano-copper slag on both natural clay and lime stabilised clay. It was observed that nano-treatment reduced the W_l and increased the W_p which led to reduction in the PI. The inter particle growth was improved with nano-copper which reduced the W_l. Uncured samples showed no significant change in the plasticity index of nano-treated lime stabilised soil whereas after 7 days of curing plasticity index was reduced to 5 times. The thickness of double diffuse layer was reduced after exchange of sodium and hydrogen ions with calcium ions which ultimately decreased the adsorbed water.

2.1.3 Nano-clay and nano-soil particles

Taha (2009) studied three different varieties of soil such as sedimentary residual soil, kaolinite and montmorillonite mineral soil. Nano-soil was produced by simple ball milling technique for each variety of soil and utilised 98% original soil with 2% nano-soil for

Fig. 4 Atterberg's limits of clay treated with nano-MgO (Taha et al., 2015)



stabilisation. An increment in the both W_l and W_p was observed. Montmorillonite soil showed higher reduction in PI as compared to residual and Kaolinite soil due to its more plastic nature. The addition of finer particles to the soil increased the water requirement to cover those particles due to their higher specific surface area and resulted in higher liquid and plastic limits. Khalid et al. (2014) modified the kaolin soil with 3% nano-kaolin dosage and found slightly raised W_l and W_p. The reduction in PI was observed after treatment. The increment in W_l and W_p was attributed to availability of higher water absorption sites due to higher specific surface area of nano-kaolin.

Similarly, Zainuddin et al. (2015) determined the impact of nano-kaolinite (3%), bentonite (5%) and sodium bentonite (2.5%) on kaolinite clay to satisfy the clay liner requirements. The inclusion of all additives led to increase in W_l and W_p of kaolinite clay whereas PI was lowered. The lowest PI was recorded with Bentonite and sodium bentonite but they were reported to increase the tendency of swelling and shrinkage. This behaviour might generate cracks which make soil unsuitable for liner. Nano-kaolinite provided higher W_l than other additives due to higher specific surface area and demanded higher water to cover the surfaces of the particles. Higher water accumulation was also due to formation of nano-pores. The lowest linear shrinkage in soil was experienced with nano-treatment which makes it more suitable for liner. Khalid et al. (2015) investigated the impact of nano-soil on consistency limits of clay of intermediate plasticity. The increase in W_l and W_p was recorded but PI was decreased. The reduction in in PI of the soil was due to higher rate of increment in W_p than W_l. Decrement of about 8% to 25% was reported in plasticity index of the treated soil after addition of 2% to 4% of nano-additive respectively. Nohani and Alimakan (2015) examined the impact of nano-clay (1% and 2%) on atterberg's limits of clay soil. The higher W_l and W_p was reported which was responsible for plasticity index reduction as the dosage increased. The increased consistency limits were due to intra particle nano-porosity which accommodated more water inside pores and resulted to higher absorption of water. Higher surface area of nano-clay led to increase the thickness of double water layer.

Also Salemi et al. (2016) modified the consistency behaviour of bentonite in Geosynthetic clay liner by partial replacement with nano-clay from 10 to 20%. Treated bentonite observed gain in W_l, W_p and PI up to 15% dosage beyond that reduction in all indices was reported but the limits were still higher than the untreated bentonite sample. The increment in consistency limits were attributed to the higher demand of water due to increased surface area of the treated bentonite. The reduction in W_l and W_p at 20% dosage was recorded due to agglomeration. Higher specific energy was experienced due to higher specific surface area of nano-clay which improved the vanderwall's force of attraction between the particles and caused them to agglomerate. Tabarsa (2017) observed increment in W_l, W_p and PI of the nano-clay-treated fine-grained soft soil (CL–ML). The increment in indices was in proportion to the nano-clay dosage. The slope of increment related to W_l was higher than W_p which triggered higher PI. Mukri et al. (2018) studied the influence of nano-kaoline on consistency limits of Kaoline soil. Nano-kaoline was partially replaced with the original kaoline as 1%, 2% and 3% by weight. Both W_l and W_p showed increment in proportion to the dosage of nano-kaoline. The rate of increment of W_p was higher than W_l which resulted in reduction PI. Baziar et al. (2018) incorporated nano-clay (1–4%) in kaoline clay and observed no change in W_l where W_p experienced reduction of 8% which led to increment in the plasticity index by 8%. Higher shape aspect ratio led to high water requirement to flow after shearing which increased the plasticity.

Safarzadeh et al. (2019) evaluated the Atterberg's indices of clay and silty clay treated with kaolinite nano-clay (0.5–2%) and reported increment in W_l, W_p and PI. The increment in W_l was more prominent than W_p. This behaviour was due to generation of more electrical charge between the particles due to higher specific surface area and caused more water absorption. Higher rate of water absorption uplifted the plasticity of soils. Zainuddin et al. (2019) improvised the bentonite soil with the help of nano-bentonite with variation in dosages as 1–3% by wt. of soil. Higher W_l and W_p was recorded which resulted in reduction of plasticity index as shown in Fig. 5. Karumanchi et al. (2020) inspected the influence of nano-clay (0.05–1%) on low compressible clay. The change in W_l and W_p were reported after treatment. PI of the treated soil reduced at initial dosages and then increased. Maximum reduction was recorded at 0.15% dosage of nano-clay. Amin et al. (2020) documented change in Atterberg's indices of sandy soil treated after nano-sand particles (1–4%). The increment in W_l and W_p observed in treated sand. The reduction in PI was recorded proportionally with the dosage of nano-sand which modified the very limit plasticity to intermediate plasticity.

2.1.4 Nano-lime and nano-cement

Prabhu et al. (2017) demonstrated the effect of nano-cement (10%) and nano-fly ash (10%) additives on highly compressible clayey soil. Nano-additives decreased the W_l and increased the W_p of the soil resulted in the reduction of plasticity index as compared to natural soil. Soil amended with non-nano-sized additives with same dosage of 10% fly ash and 10% cement also reported decrement in W_l and increment in W_p. Nano-sized additives showed higher plasticity than non-nano-sized-treated soil samples due to their high specific surface area which enhanced the water absorption capacity of soil matrix. Hussan and Al-Janabi (2018) improved the consistency of the soft clay soil after treatment with lime (4%) and nano-calcium carbonate (0.25–1% on replacement with lime). The treated soil showed reduction in W_l, W_p, and PI in proportion with the dosage of nano-lime. Less water penetration inside the soil matrix was recorded due to filling of tiny pores by nano-calcium carbonate which reduced the swelling tendency.

Al-Swaidani et al. (2019) investigated the influence of nano-calcined clay (1% and 2%) and nano-lime (0.6%) on the plastic behaviour of expansive clayey soil. The reduction in the Plasticity index was seen after treatment with nano-calcined clay. About 40% and 60%

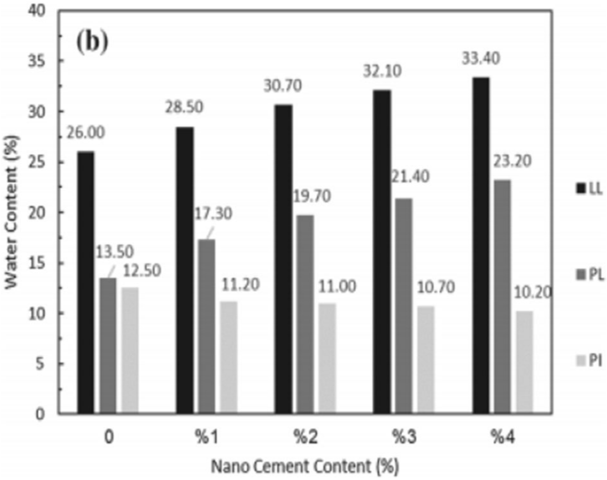


Fig. 5 Effect of nano-bentonite on consistency limits of clay (Zainuddin et al., 2019)

reduction in plasticity index of natural soil was noticed at 1% and 2% nano-calcined dosage respectively. Maximum reduction was reported after simultaneous treatment of soil with 2% nano-calcined clay with 0.6% nano-lime as shown in Fig. 6. The improvement in workability of soil was reported after treatment due to reduced plasticity. Choobbasti et al. (2019) analysed the impact of nano-calcium carbonate on kaolinite clay and reported reduction in W_l and increment in W_p. Plasticity index reduced consistently as the dosage of nano-additive was increased. Nano-treatment along with carpet waste fibres improved the mechanical behaviour of soil by reducing its plasticity which improved its shear behaviour. Calcium ion was replaced with the sodium and hydrogen ions present on the surfaces of clay particle which reduced the double water layer and reduced the plasticity. Nano-additive binds the clay particles and reduced the void spaces. Taha et al. (2019) analysed the consistency of nano-lime and lime-treated silty clay with dosages of admixtures as 0.2–1% for both. Lime-treated soil experienced increment in W_l and W_p where reduction in PI was reported. Nano-lime imparted more significant reduction in PI than lime. The initial low dosages of additives provide reduction in W_l and W_p due to reduction in thickness of double diffuse layer. But on higher dosages consistent increment was reported in both the limits which were attributed to more formation of viscous gel (*C–S–H*). This gel possessed higher water holding capacity and thus increased the limits. Tanzadeh et al. (2019) incorporated nano-lime and lime particles in the kaolinite clay individually and founded decrement in W_l and increment in W_p with both the additives whereas PI was consistently reduced up to optimum dosage. Optimum dosage for nano-lime and Lime was estimated as 1% and 4% by dry weight of soil at which maximum reduction in W_l and increment in W_p was observed beyond that minimal change was recorded. The small dosage of nano-lime imparted more significant changes in shorter duration than lime. Coarse granulation of soil matrix by additives was responsible for plasticity reduction.

Yousefi et al. (2020) evaluated increment in W_l and W_p after addition of cement and nano-cement in clayey soil. Nano-cement-treated soil experienced higher increment in consistency limits as compared to cement due to higher specific surface of nano-material. The addition of very fine particles increased water absorption and thus provided higher limits of consistency. W_p recorded higher trend of increase than W_l which led to reduction in PI

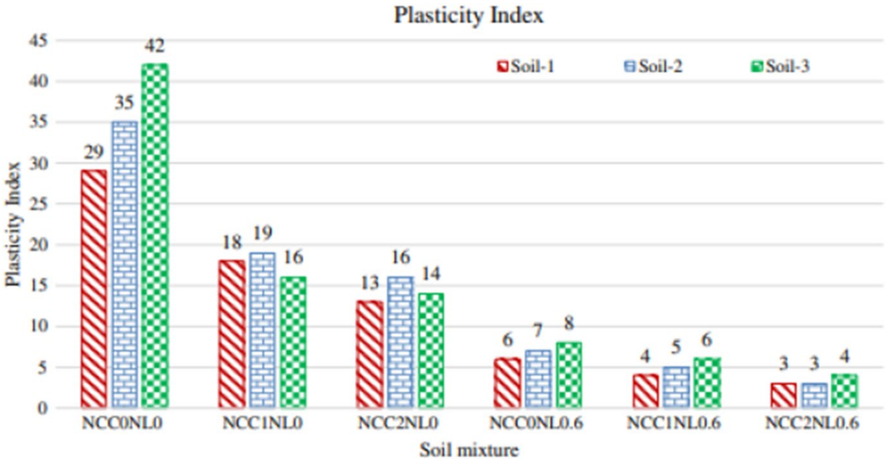


Fig. 6 PI of clays treated with nano-calcined clay and nano-lime (Al-Swaidani et al., 2019)

of the treated soil. The increment of about 28% and 24% in W_l of nano-cement and cement-treated soil, respectively, was mentioned at 4% dose. Kannan et al. (2022) treated low plastic organic soil classified as OL with the help of nano-calcium carbonate. A progressive increment in W_l, W_p and PI was stated with the inclusion of nano-additive. The remoulding of soil for performing consistency test hinders the reaction between the soil solids and additive. The stronger aggregation between the particles resisted the outside dissipation of water which could be the satisfactory reason for higher indices of consistency. Kacha et al. (2022) reported reduction in consistency indices of expansive clay (CH) treated with fly ash along with nano-lime. Plasticity was reduced to 70% at optimum dosage of 1% nano-lime with fly ash variation of 40–60% by weight of soil. Shrinkage was reduced to C60%. Calcium ion of the additive bridges with the negative charge present on the surface of the clay which resulted to the flocculation and agglomeration of the soil particles. Pozzolanic chemical reactions led to the formation of *C–S–H* gel which enhanced the bonding.

2.1.5 Nano-carbons and graphene oxide nano-sheets

Naseri et al. (2016) studied modification of geotechnical properties of cemented silty soil using Graphene oxide nano-sheets with dosage from 0.02 to 0.1% by wt. of cement and cement content was taken as 150 kg per cubic meter of soil. The W_l, W_p and PI was reduced after incorporation of nano-material as given in Table 1. Decrement in W_p was due to better packing density of soil matrix. Higher ability of the additives to absorb excess water reduced the PI of the soil matrix. Taha et al. (2018) improvised the plasticity of three different clayey samples with nano-carbons (CNTs and CNFs). Clayey samples S1, S2 and S3 were categorised by partial replacement of clay with bentonite such as 0%, 10% and 20% respectively. S1 soil experienced marginal change after treatment where S2 and S3 soils showed reduction in PI. Less significant reduction in plasticity of the clay samples was noticed with CNTs where CNFs effectively reduced the plasticity. CNFs provided more reasonable results than CNTs due to its higher aspect ratio as compared to CNTs. CNFs possessed higher density particles than clay with less specific surface area than bentonite. These fibres reflected hydrophobic nature and reduced the soaking capacity of matrix. Akbulut and Isik (2021) studied the consistency analysis on white (CH), green (CH) and red (CL) clay after the addition of nano-carbon black with dosages from 1 to 10% by soil weight. Less significant changes in W_l, W_p and PI was reported in green and red clays where white clay experienced prominent alteration. Significant reduction in W_l of white clay was observed up to 1% and then minimal change was recorded. W_p of white clays was increased up to 1% of dosage beyond that constant trend was noticed. Alteration in plasticity was attributed to the modification in double diffuse layer. Less significant modification in plasticity characteristics of green and red clay was due to non-polar nature of nano-carbon black which restricts these particles to absorb on clay plates.

Table 1 Atterberg's indices of cemented silty soil treated with graphene oxide (Naseri et al., 2016)

Soil samples	W_l (%)	W_p (%)	PI (%)
Soil + cement	50	27	23
Soil + cement + GO (0.02%)	45	24	21
Soil + cement + GO (0.05%)	39	22	17
Soil + cement + GO (0.1%)	36	21	15

2.1.6 Other nano-additives

Azzam (2014) applied nano-composite technique to modify the plasticity characteristics of clay. The polypropylene polymer (3–10%) was induced in clay and formed nano-composites of different sizes depending upon the dosage of polymer. The treated soil experienced reduction in consistency limits as the dosage was increased. The plasticity of nano-composite clay was decreased due to change in microstructure. The inter particle spacing of grain was reduced due to formation of nano-composites. The small voids were occupied by the nano-composite and imparted higher electrical attraction between particles. Hydrophobicity was exhibited by the soil grains which reduced the absorbed water. Johnson and Rangaswamy (2015) added nano-chemical (terrasil) in clay with the variation from 0.03 to 0.09% by wt. of soil. W_l and W_p increased up to 0.07% dose and then declined. PI of the soil was reduced up to optimum dosage of 0.07% and then increment was noticed. Less plastic nature of soil was obtained after treatment at optimum dosage of terrasil. Similarly, Ewa et al. (2016) studied the modification of Atterberg's indices of subgrade clayey soil by nano-chemical (Terrasil 2–8%). The treated soil had experienced reduction in W_l, W_p PI and Linear shrinkage. The reduction in indices was in proportion to the dosage of terrasil. The slope of W_l reduction was more than W_p which managed to reduce the PI.

Babu and Joseph (2016) determined the effect of nano-fly ash and nano-titanium oxide on silty clay. The additives were individually replaced by soil with the proportions of 0.5–2% by wt. of soil. The reduction in W_l, W_p and W_s was reported. W_l and W_s was reduced significantly up to 1% dosage beyond that less prominent change was recorded. The reduction trend of W_p was continuous in proportion to the dosage of both the additives. Onyelowe (2017) founded decrement in both W_l and PI of laterite soil after treatment with Nanostructured waste paper ash with dosages from 3 to 15% by wt. of soil. Maximum reduction in W_l and PI was observed at 12% dosage. Reduced PI was a result of hydration of highly pozzolanic nano-additive which provided stiffer soil matrix. Clay particles transformed to granular due to reduced adsorbed water. The reduction in plasticity was also attributed to the formation of calcium silicates and aluminates during hydration reactions.

On the basis of existing literature, it can be concluded that the inclusion of nano-additives in clay or sand reduced the PI. W_l and W_p was increased due to higher specific surface area of the nano-additives which provide more water absorption sites during hydration. The rate of increase in W_p was higher than W_l. The incorporation of nano-additives lowered the shrinkage limit of clay. Whereas Some authors documented reduction in W_l and W_p of clay with the addition of nano-additives which was attributed to alteration in the surface charges present on clay particles due to cation exchange reactions which reduced the thickness of double diffused layer. Soil particles attracted towards each other due to reduced thickness of double water layer and occupied the voids. The increase in Inter-particle contact due to decreased voids and provided more stable stiffer soil matrix. A dramatical changes in plasticity characteristics were recorded at lower dosages of nano-additives. On comparison with traditional methods such as lime and cement, lower dosages of nano-additives provided equivalent results as compared to higher dosages of conventional additives. Nano-additive along with lime or cement with lower dosages of nano-additives provided more effective reduction in plasticity as compared to individually treated soil with nanoparticles. Nanoparticles increased the reactivity of cementitious compounds such as lime and cement due to their higher specific surface area which increased the dispersion efficiency of additives in soil matrix. Higher reactivity resulted to advanced formation of cementitious compounds and resulted to greater reduction in plasticity of weak and soft soils. The effect of the nano-additives alone and with other admixtures on Atterberg's limits of soft soils is presented in tabular form in Table 2.

2.2 Compaction

The process of compaction is defined as the reduction of air voids from the soil structure with the help of compactive energy. The prime objective of compaction is to determine the maximum dry density and optimum moisture content of soil. The maximum dry density indicates the degree of denseness of the soil. The maximum dry density (γ_{dmax}) of the soil is attained at a moisture content which is termed as optimum moisture content (ω_{opt}). The process of compaction reduces the void ratio, porosity, settlement and permeability and increases the strength and bearing capacity. These compaction parameters are useful in the stability analysis of field problems such as roads, embankments, foundation of high-rise buildings, water storage structures as earthen dams. In this section, thorough study on the change in the compactive parameters of problematic soils with the inclusion of nano-additives is presented and suitable remarks are concluded at the end.

2.2.1 Nano-silica- and nano-silane-based compounds

Bahmani et al. (2014) documented the compaction parameters of residual clayey soil added with two size of nano-silica (15 nm and 80 nm) varying from 0, 0.2, 0.4, 0.8, and 1% and cement (4, 6, and 8%). They reported slight decrease in γ_{dmax} and increase in ω_{opt} of the cemented clayey soil with the increase in nano-silica content. γ_{dmax} of cemented clay added with 80 nm nano-silica was greater as compared to 15 nm size. The possibility of agglomeration with the smaller size of nano-silica was higher which led to difficulty in homogenous dispersion of particles. Due to higher specific surface area, 15 nm nano-silica provides higher ω_{opt} as compared to 80 nm size particles. Similarly, Choobbasti et al. (2015) examined the compaction parameters of sand containing various proportion of cement (5, 9, ad 14%, by weight) and nano-silica (5, 10, and 20%, by weight). At low cement content, an increase in the γ_{dmax} of sand was witnessed with the increase in dose of nano-silica because of the filling effect induced by nano-silica. Contrary to this, continuous decrement in the γ_{dmax} was reported after nano-treatment of soil at high cement content due low specific gravity of nano-silica as compared to sand. They reported increase in ω_{opt} of cement stabilised sand with the increase in nano-silica content due to its high specific surface area.

Changizi and Haddad (2016) reported 1.05, 1.1, and 1.13 times and 1.1, 1.14, and 1.2 times increase in γ_{dmax} and ω_{opt} of low compressibility soil with the addition of 0.5, 0.7 and 1% nano-silica, respectively, as shown in Fig. 7. The increase in γ_{dmax} was due to high compressibility and reduction of void ratio of nano-treated soil, whereas the absorption of moisture by nano-silica might have led to increase water demand of the mixes. Choobbasti and Kutanaei (2017) stabilised sandy soil with 6% cement and nano-silica (0%, 4%, 8% and 12% by wt. of cement). At lower dosages of nano-silica had improved the γ_{dmax} of cemented sand because of void occupied by it, whereas the low specific gravity of nanoparticles resulted into decrease in γ_{dmax} values at high content. A continuous increase in ω_{opt} of the mixes was observed with the increase in nano-silica content because of high hydration rate. Kulkarni and Mandal (2017) examined the impact of organo silane on

Table 2 Impact of nano-additives on Atterberg's limits of soil

References	Soil type	Type of nano-material and other additives	Atterberg's limits			
			W_l	W_P	P_I	W_S
Taha (2009)	Kaoline and Montmorillonite mineral Soil	Nano-kaolinite, nano-montmorillonite dosage: 0%,1%, 2% by wt. of soil	Increased	Increased	Reduced	–
Majeed and Taha (2012)	Soft Soil	nano-CuO: 0.5%, 1%nano-MgO: 0.1%, 0.2, 0.3, 0.4%nano-clay: 0.1, 0.2, 0.3, 0.4%	Reduced	Reduced	Reduced	–
Luo et al. (2012)	Clay	SSA/Cement: (3:1)15% replaced by SoilNano Al_2O_3: 0%, 1%, 2%, 3% by weight of Soil	Reduced	Reduced	Reduced	–
Taha and Taha (2012)	Clayey Soil samples with different bentonite contents	Nano-alumina: 0.05, 0.075, 0.1, 0.15, 0.3%Nano-Cu: 0.15, 0.3, 0.5, 0.7% Nano-Clay: 0.05, 0.1, 0.15, 0.3, 0.5%	–	–	Nano-Clay increased the PI; Nano-Alumina and Nano-Cu reduced the PI	–
Ugwu et al. (2013)	Black Soil, Clay, Laterite Soil	Nano-Z: (1:200), (1:150)	Reduced	Reduced	Reduced	Reduced
Azzam (2014)	Clay	Polypropylene Homo polymer: 0, 3, 6, 10% by dry wt. of Soil	Reduced	Reduced	Reduced	–
Bahmani et al. (2014)	Clay	Nano-Silica: 0, 0.2, 0.4, 0.8, 1% by wt. of Soil Cement: 4, 6, 8% by wt. of Soil	Increased	Reduced	Increased	–
Khalid et al. (2014)	Kaoline	Nano-Kaoline: 3% by weight of Soil	Increased	Increased	Reduced	–

Table 2 (continued)

References	Soil type	Type of nano-material and other additives	Atterberg's limits			
			W_l	W_P	P_I	W_S
Zainuddin et al. (2015)	Kaoline Clay	Nano-Kaolinite: 3% by wt. of ClayBentonite and Sodium bentonite: 2, 5, 7.5, 10% by wt. of kaolinite	Increased	Increased	Reduced	–
Khalid et al. (2015)	Sandy Clay Soil	Nano-Clay: 2%, 3%, 4% by weight of Soil	Increased	Increased	Reduced	–
Jassem and Tabarsa (2015)	CL–ML Soil	Nano-Clay: 0, 0.5, 1, 1.5, 2, 2.5% by wt. of Soil	Increased	Increased	Decreased	–
Kirithika et al. (2015)	Clay	Nano-Silica: 5, 10, 15%Lime: 2, 4, 6, 8, 10% by wt. of Soil	Decreased	Increased	Decreased up to 5% Nano-dosage and then marginal change noticed	–
Johnson and Rangaswamy (2015)	Soft Clay	Cement: 1, 2, 3, 4, 5% by wt. of Soil Terrasil: 0.03, 0.05, 0.07, 0.09% by wt. of Soil	Increased up to 0.07% Nano-dosage	Increased up to 0.07% Nano-dosage	Decreased up to 0.07% Nano-dosage	–
Nohani and Alimakan (2015)	Clay	Nano-Clay; 0.5, 1, 1.5, 2% by wt. of Soil	Increased	Increased	Decreased	–
Taha et al. (2015)	Clay	Nano-MgO; 0, 0.3, 0.5, 0.8, 1% by dry wt. of Soil	Decreased	Increased	Decreased	–

Table 2 (continued)

References	Soil type	Type of nano-material and other additives	Atterberg's limits			
			W_l	W_P	P_I	W_S
Moharram et al. (2016)	Clay	Nano-Silica: 0%, 0.5%, 1%, 1.5%. 2%, 2.5%, 3% by dry wt. of SoilNano-Kaolinite: 0%, 0.5%, 1%, 1.5%. 2%, 2.5%, 3% by dry wt. of Soil	Increased	Increased	Decreased	–
Ewa et al. (2016)	Silty Clay	Terrasil: 0%, 2%, 4%, 6%, 8%	Decreased	Decreased	Decreased	–
Ghasabkolaei et al. (2016)	Clay	Cement: 9% Nano-Silica: 1%, 1.5%, 2%, 3%	Cement Increased the LL	Cement: Increased the PL	Cement Decreased the PI where Nano-Silica Increased PI	–
Hanson et al. (2016)	CL, CH and Bentonite	Nano-Silica: 0.1, 0.2, 0.5, and 1%Nano-Silver: 0.1, 0.2, 0.5 and 1%	Decreased	Decreased	Decreased	–
Naseri et al. (2016)	Silty Soil	Graphene oxide Nano-sheets: 0.02%, 0.05%, 0.1% wt. of cement Cement: 150 kg per cubic meter of Soil	Decreased	Decreased	Decreased	–
Salemi et al. (2016)	Bentonite in Geosynthetic Clay liner	Nano-Clay: 0%, 10%, 15%, 20% of bentonite content	Increased up to 15% Nano-dosage	Increased up to 15% Nano-dosage	Increased up to 15% Nano-dosage	–
Babu and Joseph (2016)	Silty Clay	Nano-TiO_2, Nano-Fly Ash: 0.5%, 1% and 2% by weight of Soil for both	Decreased	Decreased	–	Decreased

Table 2 (continued)

References	Soil type	Type of nano-material and other additives	Atterberg's limits			
			W_{l}	W_{P}	P_{I}	W_{S}
Coo et al. (2016)	Clay	Nano-CuO and Nano-Al_2O_3: 2%, 4%, 6% by dry wt. of Soil for both	–	–	–	Increased
Kulkarni and Mandal (2017)	Medium expansive Silty Soil	Fly Ash: 10%, 20%, 30%, 40%, 50% by dry wt. of Soil Nano-material: (1:100), (1:225), (1:400), (1:600) dilution ratio by volume	Decreased	Decreased	–	–
Changizi and Haddad (2017)	Soft Clay	Nano-Silica: 0.5%, 0.7%, 1%	Decreased	Increased	Decreased	Decreased
Prabhu et al. (2017)	Highly compressible Clay	Nano-Fly Ash:10% Nano-Cement: 10%	Decreased	Increased	Decreased	–
Onyelowe (2017)	Laterite Soil	Nano-structured waste paper ash: 3%, 6%, 9%, 12%, 15%Curing time: 7, 14, 28 days	Initial Increased up to 3% Nano-dosage and then Reduced	Initial Increased up to 3% Nano-dosage and then Reduced	Initial Increased up to 3% Nano-dosage and then Reduced	–
García et al. (2017)	Lacustrine highly compressible Clay	Nano-Silica: 0.5%, 0.7%, 1%, 3% by dry wt. of Soil	Slightly Increased	Slightly Increased	–	–
Singh (2017)	Clay	Terrasil:1%, 1.5%, 2%	Decreased up to 1.5% Nano-dosage and then Increased	–	Decreased up to 1.5% Nano-dosage and then Increased	–
Tabarsa (2017)	CL–ML	Nano-Clay: 0%, 0.5%, 1%, 1.5%, 2%, 2.5%, 3%, 3.5%, 4%	Increased	Increased	Increased	–

Table 2 (continued)

References	Soil type	Type of nano-material and other additives	Atterberg's limits			
			W_l	W_P	P_I	W_S
Eswaramoorthi et al. (2017)	Clay	Nano-Silica: 5%, 10%, 15%Nano-Lime: 2%, 6%, 10% Curing period: 7 days	Decreased	Increased	Decreased	–
Shaker (2018)	Clay	Nano-Silica: 0.5, 1, 1.5, 2 and 3% by weight of Soil	Increased	Slightly Increased	Increased	–
Taha et al. (2018)	Clay	Bentonite: 0%, 10%, 20% by dry wt. of SoilNano-Carbon (CNFs and CNTs): 0.05%, 0.075%, 0.10%, 0.20%	–	–	Decreased	–
Mukri et al. (2018)	Kaoline Soil	Nano-Kaoline: 0%, 1%, 2%, 3%	Increased	Increased	Decreased	–
Onyelowe and Duc (2018)	Expansive Soil	Cement: 5% Nano-Biomass Ash: 5%, 10%, 15%	Decreased	–	Decreased	–
Hussan and Al-Janabi (2018)	Soft Soil	Soil + 4% Lime with 0.25%, 0.5%, 1% Nano-$CaCO_3$ as replacement of Lime added Curing period: 7, 14, 28 days	Decreased	Decreased	Decreased	–
Nisha and Roy (2018)	Local Soil	Nano-Silica: 5%, 10%, 15%, 20%, 25%, 30% Bentonite: 10%, 15%, 20%, 25%, 30%, 35%	Increased	Increased	Increased	–

Table 2 (continued)

References	Soil type	Type of nano-material and other additives	Atterberg's limits			
			W_l	W_P	P_I	W_S
Jahromi and Zahedi (2018)	Clay	Nano-Aluminium: 2%, 4%, 6% by wt. of cement used Cement: 4% and 8% by weight of Soil	–	–	Decreased	–
Baziar et al. (2018)	Kaolinite Clay + Sand	Nano-Clay: 1%, 2%, 3%, 4%1:9CS and 1:4CS Soil samples prepared for testing	Constant	Decreased	Increased	–
Al-Swaidani et al. (2019)	Expansive Clayey Soil	Nano-Calcined Clay: 0%, 1%, 2% by wt. of Soil Nano-Lime: 0.6% by wt. of Soil	–	–	Decreased	–
Ahmadi and Shafiee (2019)	Clayey Soil	Nano-Silica: 0–6%, 28 days curing time Micro Silica: 0–6%	Nano-Silica Increased the LL; Micro Silica showed no change	–	Nano-Silica Increased the PI; Micro Silica showed no change	–
Choobbasti et al. (2019)	Clayey Soil	Nano-$CaCO_3$: 0%, 0.4%, 0.8%, 1.2% Carpet waste fibres: 0%, 0.2%, 0.4%, 0.6%	Decreased	Decreased	Decreased	–
Kirithika and Stalin (2019)	Highly Compressible Clay	Nano-Cu slag:1%, 2%, 3% Curing period: Immediate and 7 days	Decreased	Increased	Decreased	–
Safarzadeh et al. (2019)	Clay and Silt	Nano-Kaolinite: 0%, 0.5%, 1%, 1.5%, 2% Curing period: 7 days	Increased	Increased	Increased	–

Table 2 (continued)

References	Soil type	Type of nano-material and other additives	Atterberg's limits			
			W_{l}	W_{P}	P_{I}	W_{S}
Parsakhoo (2019)	High plastic Clay (CH) and low plastic Clay (CL)	Nano-Silica + Horse-tail Ash:0.5% + 1%, 1% + 2%, 1.5% + 3%, 2% + 4% Curing period: 7, 14, 28 days sample analysis	Increased for CH type Increased up to mix 2 and then reduced for CL type	Increases for CH type Increased up to mix 2 and then reduced for CL type	Decreased for CH type Decreased up to mix 2 and then increased for CL type	–
Taha et al. (2019)	Silty Clay	Nano-Lime and Lime: 0.2–1% of dry wt. of Soil Curing period: 1, 28, 60 days analysis	Increased	Increased	Decreased up to 0.5% Nano-dosage and then raised	–
Tanzadeh et al. (2019)	Clay	Lime: 2%, 4%, 8%, 16% Nano-Lime: 0.5%, 1%, 2%, 4%	Decreased (more effect by Nano-Lime than Lime)	Increased (more effect by Nano-Lime than Lime)	Decreased (more effect by Nano-Lime than Lime)	–
Zainuddin et al. (2019)	Bentonite	Nano-Bentonite:0%, 1%, 2%, 3%	Increased	Increased	Decreased	–
Sobhani Nezhad et al. (2020)	Gas oil contaminated Clay	Nano-Silica: 1%, 2%, 3% by weight of SoilHydrated Lime: 1%, 2%, 3% by weight of Soil for mix (1:1) used	Increased	Increased	Decreased	–
Yousefi et al. (2020)	Clay	Nano-Cement and Cement: 1%, 2%, 3% and 4% for both by weight of Soil	Increased	Increased	Decreased	–
Siddiki and Singh (2020)	Clay	Nano-Aluminium oxide: 0.5%, 1%, 1.5%, 2% and 2.5% by weight of Soil	Decreased	Decreased	Increased	–

Table 2 (continued)

References	Soil type	Type of nano-material and other additives	Atterberg's limits			
			W_l	W_P	P_I	W_S
Karumanchi et al. (2020)	Clay Soil with low compressibility	Nano-Clay: 0.2%, 0.4%, 0.6%, 0.8% 1%	Increased	Increased	Decreased up to 0.15% Nano-dosage and then raised	–
Amin et al. (2020)	Sandy Soil	Nano-Sand: 1–4%	Increased	Increased	Decreased	–
Ghavami et al. (2021)	Clay	Nano-Silica: (0.5–2%) Silica fume: (5–20%), Cement kiln dust:15%	Increased by Nano-Silica and Decreased by Silica fume	Decreased by both Nano-Silica and Silica fume	Increased by Nano-Silica and Reduced by Silica fume	–
Al-Swaidani and Meziab (2021)	Expansive Soil	Nano-natural pozzolona: (1%, 2%) and Nano-Lime (0.6%)	–	–	Decreased by both additives	–
Akbulut and Isik (2021)	White, green and red Clays	Nano-carbon-black:1–10%	No change in red and green Clay, Decreased in white Clay	Minimal change in red and green Clay, Increased in white Clay	Less change in red and green Clay, reduction in white Clay	–
Kalhor et al. (2022)	Clay	Nano-Silica: 1–4% by weight of Soil	Increased	Increased	Decreased	–
Kannan et al. (2022)	Low plastic organic Soil (OL)	Nano-calcium carbonate: 0.2–0.8% by wt. of Soil	Increased	Increased	Increased	–
Kacha et al. (2022)	Expansive Soil (CH)	Nano-Lime:0–1% by wt. of Soil Fly ash:20–60% by wt. of Soil	Decreased	Increased	Decreased	–

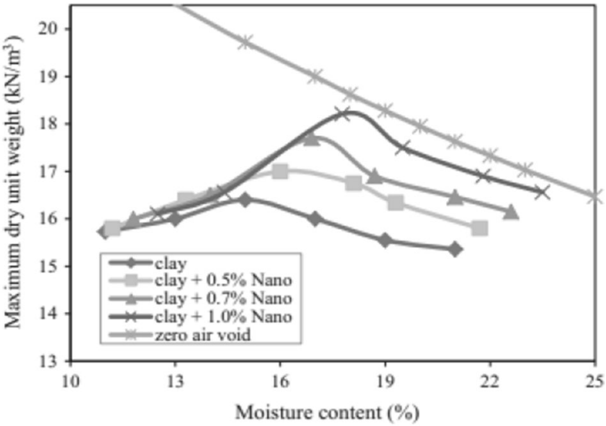


Fig. 7 Modification of γ_{dmax} of clay-treated nano-silica (Changizi & Haddad, 2016)

compaction behaviour of fly ash-silty sand mixes. The organo silane was diluted in ratio of 1:100, 1:225, 1:400, and 1:600 with water. Slight increase in the γ_{dmax} of mixes was reported with addition of organo silane in ratio of 1:100 and 1:225 as compared to 1:400 and 1:600 ratios. The decrease in ω_{opt} of mixes was marginal with the increase in dilution ratio. The rearrangement of the particles due to formation of siloxane bonds and hydrophobicity of the mixes had resulted in such observations. Eswaramoorthi et al. (2017) analysed the impact of nano-sized silica (5%) and nano-lime (10%) on clayey soil. Higher fineness was offered by the nano-additives which alters the compactive parameters. Nano-amended soil shows reduction in γ_{dmax} and increment in ω_{opt} as compared to non-nano-sized same additives as well as natural soil. Shoospasha et al. (2018) performed the compaction test on cemented sandy soil after treating it with nano-silica (4–8% by soil wt). Reduction in γ_{dmax} was reported due to increase in porosity. ω_{opt} showed increment due to raised demand of moisture caused by the higher specific surface area of nano-silica. Nisha and Roy (2018) determined the influence of nano-silica and bentonite on clay soil sample with the variation in dosage of 5–30% and 10–35% for nano-silica and bentonite respectively. The increase in ω_{opt} and reduction in γ_{dmax} was reported after treatment.

Malik et al. (2019) observed increase in ω_{opt} and decline in γ_{dmax} with the increase in nano-silica content from 5 to 15%. The dry density was decreased on higher nano-silica dosages (10% and 15%). But initially at 5% it was improved due to filling of pore spaces in the soil structure. The reduction was might be due to agglomeration by the nano-silica present in the absurd amount due to its higher specific surface charges. The agglomeration phenomenon reduced the density due to formation of lumps and thus influences the density. Ahmadi and Shafiee (2019) founded increase in ω_{opt} and reduction in γ_{dmax} after treating clayey soil with the nano- and micro-size silica particles. Less significant change was noticed up to 1% dosage whereas above 1% more prominent changes were observed. Increment of 13% and 6% was noticed in ω_{opt} after treating soil with nano-silica and Micro silica, respectively. Kalhor et al. (2019) analysed the changes in compactive behaviour of clayey soil incorporated with nano-silica and found increase in ω_{opt} and decrement in γ_{dmax} as the nano-content in the soil increased. The soil particles were replaced by low specific gravity particles of nano-silica which reduced the density of the nano-amended soil. While the specific surface area of the soil was very high which showed higher water absorption tendency to remain stable after hydrolysis which increased ω_{opt} of the soil. Parsakhoo (2019) amended highly compressible clay and low compressible clayey soil with nano-silica along with horsetail ash. The increment in ω_{opt} and γ_{dmax} of soil was seen. Higher specific surface of the nano-additive required more water to hydrate which increased the water absorption capacity of the treated soil and thus increased ω_{opt}. The increase in γ_{dmax} was attributed to the filling of voids in soil ash matrix by the nano-particles. Tomar et al. (2019) evaluated the compactive parameters of nano-silica and polypropylene fibres (PPF)-treated clayey soil. A continuous reduction in γ_{dmax} and rise in ω_{opt} was noticed after treatment with both the additives. The reduction in γ_{dmax} was attributed to the replacement of lows density particles of nano-silica and PPF with high density soil particles.

In the same way, Sarli et al. (2020) demonstrated reduction in γ_{dmax} and increment in ω_{opt} in loess soil treated with nano-silica along with recycled polyester fibre. The dosage of 2%, 4% and 6% by wt. of soil in the proportion of 33% and 50% was used to stabilise soil. As the content of additives was increased, γ_{dmax} reduces and ω_{opt} increases. Sobhani Nezhad et al. (2020) investigated the influence of nano-silica and hydrated lime on the gas oil contaminated clayey soil. Natural soil after gas oil contamination showed reduction in γ_{dmax} and ω_{opt} due to higher viscosity of oil than water which restricted the lubrication between the soil particles. Nano-silica-treated soil had shifted the curve rightwards and showed increment in ω_{opt} and declined in γ_{dmax}. This change in behaviour was attributed to higher specific surface area of nano-additive which enhanced the water absorption and resulted increase ω_{opt}. The reduction in γ_{dmax} was due to replacement of low specific gravity nano-particles from natural soil. The hydrated lime also showed the same trend of decrement in γ_{dmax} and increment in ω_{opt}. The high-water demand to satisfy the pozzolanic reactions between Calcium hydroxide and silica particles present in soil during the hydration process causes rise in ω_{opt}. The reduction in γ_{dmax} was due to formation of more flocculated type of structure which accommodated higher volume and thus reduced the density. Simultaneous treatment of the additives shows further decrement in γ_{dmax} and increment in ω_{opt} due to intensification of cation exchange reactions due to availability of more silica particles which required more water to satisfy the hydroxyl demand during reaction with calcium ions.

Ghavami et al. (2021) studied the behaviour low compressible clay along with cement kiln dust. Nano-silica and Silica fume was replaced with cement kiln dust. Silica fume shows significant reduction in γ_{dmax} and rise in ω_{opt}. The change in particle surface area of the soil matrix led to rise in ω_{opt} whereas, reduction in γ_{dmax} was attributed to the lower specific gravity of the silica fume particles than cement kiln dust. Nano-silica showed marginally reduction in γ_{dmax} and increment in ω_{opt} when replaced with Cement kiln dust. The agglomeration effect was noticed as the nano-content was increase which caused reduction γ_{dmax} profile. Bargi et al. (2021) examined the behaviour of three different fines of soil (silt, Kaolinite, Bentonite) with the addition of three different types of silica products (Silica fume, nano-silica200, nano-silica 380). The higher cement content of 8% was required by bentonite fine to attain γ_{dmax}, whereas 7% was demanded by the other two because of its higher plasticity. The additives showed reduction in γ_{dmax} and increment in ω_{opt} at fixed dose of 0.5% by wt. of cement and a comparison was prepared. γ_{dmax} reduced by 6%, 6.5% and 3% and ω_{opt} showed increment of 3%, 2.5% and 0.5% with nano-silica 380, nano-silica 200 and silica fume, respectively as compared to control mixture of cemented silt fine soil. The C–S–G gel formation dissipated higher compaction energy which reduced the compactibility. The increase in ω_{opt} was due to higher specific surface area of the additives which enhances the water reaction tendency. Higher nano-silica 200 dose above 0.5% showed effect of agglomeration which further reduced the density.

Kalhor et al. (2022) stated reduction in γ_{dmax} and increment in ω_{opt} of clayey soil treated with nano-silica with dosages as 1–4% by weight of soil. The inclusion of nano-silica increased the water absorption potential of the treated soil due to its hydrophilic nature. The reduction in γ_{dmax} was attributed to the low weight of nano-silica particles as compared to the particles of soil.

2.2.2 Nano-copper, nano-alumina and nano-magnesium

Majeed and Taha (2012) performed compaction tests on low compressible organic soil incorporated with 0.001% and 0.002% (by dry wt. of soil) nano-CuO, nano-MgO and nano-clay. The inclusion of nanoparticles increased γ_{dmax} and ω_{opt} of the soil. Nano-CuO showed higher γ_{dmax} as compared to other nano-additives. In a similar way, Taha and Taha (2012) examined the effect of nano-clay, nano-alumina and nano-Cu varying from 0.05–0.5, 0.05–0.3, and 0.15–0.7% ((by dry wt. of soil) respectively, on the clayey soil incorporated with 0–20% bentonite. A marginal change in the γ_{dmax} and ω_{opt} of clayey soil were observed with the inclusion of nano-clay, nano-alumina and nano-Cu. Nano-alumina showed insignificant change in ω_{opt} of clayey soil added with 5% and 10% bentonite, whereas slight increase in γ_{dmax} was observed with addition of nano-alumina up to 0.1%. Further incorporation of nano-alumina led to decrease in the γ_{dmax} of the mixes. The maximum increase in the γ_{dmax} of the clayey soil- bentonite mixes were observed with the inclusion of nano-Cu in range of 0.3–0.5%, whereas w_{opt} was found independent of the nano-Cu content. The addition of nano-Cu showed significant increase in the γ_{dmax} of the mixes as compared to other nano-additives because of its higher particle density. The agglomeration effect was noticed, when content of nano-additives increased beyond the optimum limit, which may be reason behind the reduction in γ_{dmax}. Luo et al. (2012) documented reduction in γ_{dmax} and increase in ω_{opt} of SSA/cement stabilised clay with the inclusion of nano-alumina. The low specific gravity and high specific surface area of nano-alumina was responsible for the respective behaviour.

Majeed et al. (2014) investigated the effect of nano-CuO (0.2–1%), nano-clay (0.05–0.3%) and nano-MgO (0.1–0.4%) on compaction behaviour of low compressible organic soil and highly compressible clay. It was found that the inclusion of nano-additives resulted in decrease ω_{opt} of highly compressible clay due to absorption of water from the moist soil. Whereas, increase in ω_{opt} of low compressible organic soil reported with the increase in nano-additives because of accumulation of water with in the flocculated structure of matrix. Contrary to this, a continuous increase in γ_{dmax} was observed with substitution of nano-additives in both type of soil. The high particle density of the nano-additives and reduction in the porosity was cited as reason for such behaviour. Maximum improvement in the density was found for nano-CuO treated highly compressible clay. Majeed and Taha (2016) compared the effect of nano-CuO, nano-Al_2O_3, and nano-MgO on the compaction behaviour of low compressible organic soil and highly compressible clay. For organic soil, marginal increase in the γ_{dmax} was observed with addition of nano-additives. This marginal improvement in the γ_{dmax} was due to high particle densities of nano-additives as compared to soil, whereas, the inclusion of nano-additives led to significant rise in ω_{opt} due to flocculated structure of the matrix. For highly compressible clayey soil, the incorporation of nano-additives resulted into increase in γ_{dmax} and decrease in ω_{opt}. The nano-CuO-treated clayey soil showed maximum γ_{dmax} values as compared to other treatment. Jahromi and Zahedi (2018) recorded reduction in γ_{dmax} and increase in ω_{opt} of clay amended with cement (4% and 8%). However further incorporation of cemented clay with nano-aluminium (2–6% by cement wt.) showed vice versa effects on compactive parameters.

Kirithika and Stalin (2019) determined the compactive characteristics of the original and lime stabilised clayey soil after incorporation of nano-copper slag. The increment in ω_{opt} and reduction in γ_{dmax} was seen with the increase in nano-content for both lime or non-lime treated clay soil. The rise in ω_{opt} was attributed to availability of higher water absorption surface sites during the hydration process due to higher specific surface area of the nano-additive. The nano-material content above the optimum range led to agglomeration of the particles which increased the void ratio and reduces the density. Mir and Reddy (2021) evaluated the impact of nano-alumina on low compressible silt. The increment in γ_{dmax} and decrement in ω_{opt} was reported up to the optimum dose of 1.5% beyond which vice versa results were noticed. Higher γ_{dmax} and lower ω_{opt} was due to filling of voids which reduced the porosity. Higher specific surface area of nano-alumina caused higher rate of water absorption above optimum dose due to agglomeration of particles.

2.2.3 Nano-clay and other nano-soil particles

Khalid et al. (2014) reported increase in γ_{dmax} and decrease in ω_{opt} of kaoline soil with the inclusion of 3% nano-kaoline. Zainuddin et al. (2015) compared the effect of nano-kaolinite (3%), bentonite (2.5–10%) and sodium bentonite (2.5–10%) on the compaction parameters of kaolinite soil. The maximum improvement in γ_{dmax} was reported for kaolinite soil incorporated with 3% nano-kaolinite. Jassem and Tabarsa (2015) assessed the impact of polypropylene fibres of 6 to 18 mm length varying from 0 to 1.5% in step of 0.3% and nano-clay varying from 0 to 2.5% in step of 0.5% on the compaction parameters of CL–ML. MDD of the CL–ML decreased with increasing the content of nano-clay and polypropylene fibres, this was accredited to low specific gravity of nano-clay and polypropylene fibres as compared to soil. The inclusion of nano-clay and polypropylene fibres increased ω_{opt} of the soil, which was attributed to the high-water absorption of capacity of nano-clay and polypropylene fibres compared to that of soil.

In contrary, the increment in γ_{dmax} and decrement in ω_{opt} of kaoline soil treated with 0, 1, 2 and 3% nano-kaoline was seen by Mukri et al. (2018). The higher particle density and filling of voids of soil by nano-kaoline might have led to such results. Baziar et al. (2018) evaluated the influence of nano-clay (1–4%) on clayey sand samples. γ_{dmax} shows increment up to 3% dose and then declines. Agglomeration effect was observed on higher dosage which increases the porosity. Fluctuation in ω_{opt} was recorded between 9 and 12% dose of nano-clay. Al-Swaidani et al. (2019) studied the impact of nano-calcined clay and nano-lime on the expansive clayey soil, replacement of soil with nano-lime reduced the γ_{dmax} and increase in ω_{opt} was detected caused due to higher affinity of lime towards water which increased the water retention capacity of soil. Treating soil with nano-calcined clay alone shows increment in γ_{dmax} and reduction in ω_{opt} due to its lower affinity to water which reduced the water retention in the soil, also the specific gravity of the Nano clacined clay was on higher side than original soil which leads to increase in the density. Safarzadeh et al. (2019) amended two silts and one clay sample with the nano-clay in the variation of 0.5–2% dose. The increment in γ_{dmax} and reduction in ω_{opt} was reported with the increase in the dosage. Zainuddin et al. (2019) observed the increment in γ_{dmax} and reduction in ω_{opt} after incorporation of nano-bentonite in bentonite soil. As the content of nano-bentonite increased more impact was noticed on compactive parameters. The replacement of large space voids with nano-bentonite resulted change in compaction parameters. Karumanchi et al. (2020) incorporated soft clayey soil with the nano-clay particles with the variation of 0.05% to 0.5% dosage and noticed increase in γ_{dmax} up to 0.15% of dosage. Whereas, a continuous decrease in ω_{opt} was reported. Optimum dosage was reported as 0.15% of nano-clay.

2.2.4 Nano-lime and nano-cement

Prabhu et al. (2017) compared the effect of nano- and non-nano-sized cement-fly ash on clayey soil. They reported that the inclusion of nano-sized fly ash and cement in the clayey soil reduced the γ_{dmax} and increased ω_{opt} as compare to non-nano-sized fly ash–cement stabilised clayey soil. The high specific surface area of nano-additive's led to such observation. Hussan and Al-Janabi (2018) compared the compaction behaviour of lime treated soft soil incorporated with 0.25%, 0.5%, and 1% nano-$CaCO_3$. They reported increase in the γ_{dmax} of lime treated soil with the addition of nano-$CaCO_3$ up to 0.5%. Taha et al. (2019) incorporated nano-lime and lime particles to silty clayey soil. They reported slight increase in γ_{dmax} and reduction in ω_{opt} of soil after lime treatment whereas, nano-lime showed increment in both γ_{dmax} and ω_{opt} up to optimum dosage limit (0.5%) beyond which vice versa had occurred as shown in given Fig. 8. The finer particles of the nano-additive had occupied the voids and acted as a better lubricating agent which may be the reason for rise in γ_{dmax}. Whereas, ω_{opt} increment was attributed to the higher rate of consumption of water. Tanzadeh et al. (2019) evaluated the behaviour of compactive parameters of clayey soil with the inclusion of nano-lime and lime particles. The increment in γ_{dmax} and decrement in ω_{opt} was observed after treatment with both the additives. The change in gradation of the clay matrix provides coarser and stronger structure which led to rise in the γ_{dmax}. The generation of heat due to chemical reaction with the additives resulted in the decrease of ω_{opt}. The suggested optimum dose of nano-lime was 1% and lime was 4%.

Yousefi et al. (2020) resulted increment in ω_{opt} and reduction in γ_{dmax} after stabilising clayey soil with cement and nano-cement individually. About 13% and 18% increment in ω_{opt} was noticed with cement and nano-cement treated soil at 4% dosage respectively. The increase in ω_{opt} and reduction in γ_{dmax} was attributed to higher absorption of water due to presence of nano-cement which had higher specific surface area. Bhadra and Leander (2020) observed decrement in γ_{dmax} of lime treated clay after amending it with

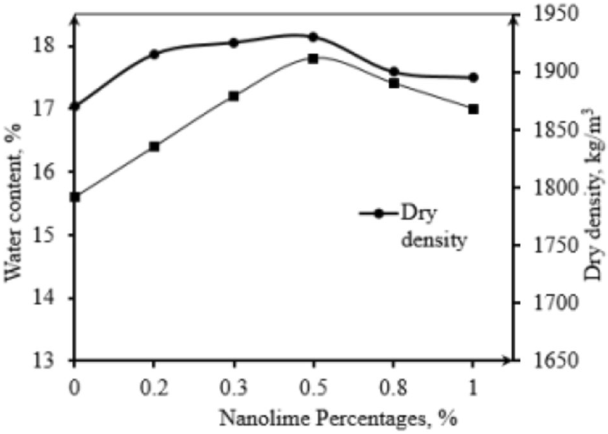


Fig. 8 Influence of nano-lime on compaction parameters of silty clay (Taha et al., 2019)

nano-calcium silicate at initial dose of 0.2%. A continuous increase in ω_{opt} of the matrix was seen which was attributed to the formation of flocculated structure which caused difficulty in compaction and raised the water demand for hydration at initial phase of low nano-dose. Higher dose more than 0.2% showed increase in γ_{dmax}. Al-Swaidani and Meziab (2021) examined behaviour of three types of soil (CL, MH, CH) with the inclusion of nano-lime (0.6%) and nano-natural pozzolana (0%, 1%, 2%). The nano-lime treated soil had provided higher ω_{opt} and lower γ_{dmax} than untreated soils. This behaviour was attributed to replacement of lower specific gravity particles of nano-lime with the soil and higher capacity of water retention. Nano-lime along with nano-natural pozzolana showed increase in γ_{dmax} and decline in ω_{opt} but the parameters were found somehow around the untreated soils. This was due to higher specific gravity of pozzolana and lesser water affinity. Kannan et al. (2022) incorporated nano-calcium carbonate in low plastic organic soil and reported reduction in ω_{opt} and marginal decrement in γ_{dmax}. Nanoparticles filled the pore spaces between the particles due to its small size and increased the aggregation which restricted the easy imbibing of water inside the soil structure. The aggregation of the soil particles resisted thecompactive effort and caused marginal decrement in γ_{dmax}.

2.2.5 Nano-carbons and graphene oxide

Naseri et al. (2016) incorporated graphene oxide nano-sheets (0.02%, 0.05%, 0.1%, by weight of cement) in the silty soil stabilised with 150 kg/cu.m of cement. The reaction between graphene oxide nano-sheets and cemented clay led the formation of C–H–S gel and compacted the structure of matrix was seen which resulted an increase in γ_{dmax}, whereas formation of interface bonds and C–H–S gel led to decrease in ω_{opt} of the cement treated soil by reducing the pores. Alsharef et al. (2016) evaluated the effect of multi walled carbon nano-tubes and carbon nano-fibres of various percentage (0.05, 0.075, 0.1, and 0.2% by wt. of soil) on the compaction behaviour of clayey sand. Up to 0.075% incorporation of nano-carbons in clayey sand, increment in γ_{dmax} and decrement in ω_{opt} was witnessed which can be seen in Fig. 9. The reduction in water content was accredited to filling

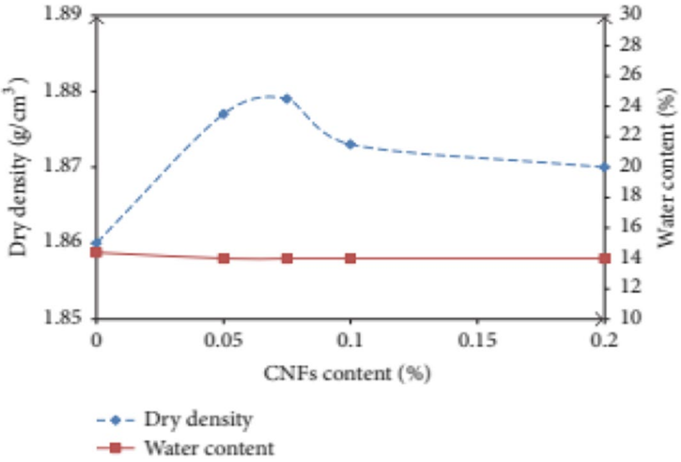


Fig. 9 Alteration in dry density and water content with content of CNFs (Alsharef et al., 2016)

of the pores by nano-additives. Further inclusion of nano-carbons led to decrease in γ_{dmax} and Increase in ω_{opt} of the mixes.

In the same way, Taha and Alsharef (2017) reported the maximum γ_{dmax} and lowest ω_{opt} values at 0.075% inclusion of nano-carbon tubes and carbon nano-fibres in low compressible clayey soil. At the optimum dose, γ_{dmax} of carbon nano-fibres treated clay was higher compared to nano-carbon tubes because of greater diameter and length of carbon nano-fibres. Taha et al. (2018) evaluated the effect of carbon nano-tubes and carbon nano-fibres on the compaction parameters of low plasticity clay incorporated with 10 and 20% bentonite. With the increase in carbon nano-tubes content, negligible decrease in the ω_{opt} of clayey soil mixed with 10 and 20% bentonite was reported, whereas the increase in carbon nano-fibres content led to decrease in ω_{opt} of the mix. The lowering of ω_{opt} was due to rearrangement of soil particles and filling of the void with addition of nano-additives. The addition of carbon nano-tubes and carbon nano-fibres up to 0.1% resulted in increased γ_{dmax} of the mixes. Beyond 0.1% content, the effect of nano-additives had become less prominent. The increase in γ_{dmax} up to 0.01% content was due to well dispersion of the nano-additive and filling of the pores. The lowering in γ_{dmax} values beyond optimum dose was attributed to agglomeration phenomena. Overall, the effect of carbon nano-fibres on the γ_{dmax} of mix was more predominant as compared to carbon nano-tubes because of its higher diameter and length. Li et al. (2021) incorporated nano-graphene oxide in Cemented loess soil and founds higher γ_{dmax} and lower ω_{opt} than natural. The reduction in pores was noticed due to formation of C–S–G gel and denser soil matrix was achieved.

2.2.6 Other nano-additives

Azzam (2014) observed increase in γ_{dmax} and decrease in ω_{opt} with the inclusion of polypropylene homopolymer in the clayey soil. The increment in density was attributed to decrease in inter-particle space and ion-exchange at the micro level. The increase in the net electrical attraction reduced the void and improved the cohesion between the particles was given as a reason for decrease in water content. Babu and Joseph (2016) improved the compaction behaviour of silty clay with nano-fly ash and nano-TiO_2 (0.5–2%). Increase in γ_{dmax} and decline in ω_{opt} was noticed with both the additives in individual treatment. Ewa et al. (2016) observed increase in γ_{dmax} and ω_{opt} of clayey soil with the addition of terrasil up to 6%. The increase in γ_{dmax} of the mixes was credited to the formation of siloxane bond between the clay particles and terrasil.

Onyelowe (2017) treated the lateritic soil with nanostructured waste paper ash (3%, 6%, 9%, 12%, and 15%, by dry weight of soil) and documented the optimum dose of 9%. Increase in γ_{dmax} and decrease in ω_{opt} at optimum content was attributed to cation exchange reaction and void filled with nano-additive. Continuous increase in γ_{dmax} and decrease in ω_{opt} of highly compressible clayey soil treated with 1%, 1.5%, and 2% Terrasil was observed by Singh (2017). The effect of nano-waste paper ash, nano-palm bunch ash, nano-snail shell ash, nano-periwinkle ash, and nano-quarry dust on the compaction behaviour of lateritic soil incorporated with 5% cement were studied by Onyelowe and Duc (2018). The cemented soil was mixed with 5, 10, and 15% nano-biomasses, separately. They reported continue increase in γ_{dmax} of the soil with the increase in percentage of nano-biomasses except nano-waste paper ash (at 5% content). The increase in γ_{dmax} with an increase in the nano-biomasses content was observed due to cation exchange reaction, filling of the pores and flocculation. Jassal (2020) blended the alluvial soil with terrasil and zycobond. Up to 0.9 kg/m^3 inclusion of both additives led to increase in γ_{dmax} and ω_{opt} further than decline was noticed. The formation of alkyl siloxane bond layer took place after reaction with the soil particles which provided better compaction properties.

From the past studies, it can be concluded that nano-amended soil (coarse grained such as sand, silt) provides denser and stiffer soil matrix. Nano-particles reduces both nano- and micro-pores by filling the void spaces uniformly which decreases the inter particle spacing and hence increases the γ_{dmax}. The products formed after hydration reactions in the form of *C–S–H*, *C–A–S–H* gels etc. improved the bonding between the soil particles and thus showed stiffer and denser soil structure. The aggregations between the soil particles restricted the entry of water inside the soil matrix and thus reduced ω_{opt}. Up to optimum dosage, the addition of nano-additives can increase the γ_{dmax} and reduce ω_{opt} of weak soils. Beyond that vice versa occurs due to agglomeration effect at higher dosages. The agglomeration problem forms non uniform large unstable lumps which causes formation of large size voids and reduces the density. Nano-treated fine grained soil experienced reduction in γ_{dmax} and increment in ω_{opt} after nano-stabilisation. The decrement in γ_{dmax} was attributed to the replacement of higher specific gravity particles of soil with lower specific gravity of nanoparticle. Whereas increment in ω_{opt} was due to higher specific surface area of nanoparticles which caused higher water absorption potential during hydration. The effect of the nano-additives alone and with other admixtures on compaction behaviour of soils is presented in tabular form in Table 3.

2.3 Consolidation

The effect of Nanoparticles on the consolidation parameters such as compression index, coefficient of consolidation, settlement, and void ratio of problematic soils has been discussed in this section.

2.3.1 Comparative analysis of major nano-additives

Iranpour and Haddad (2016) determined the impact of nano-clay, nano-silica, nano-copper and nano-alumina on the collapse potential of clay samples S3 and S5 which are classified as low compressible clay. Nanoparticles were added with the dosages as 0.1–0.6% by weight of soil. It was reported that all the nanoparticles were capable in the reduction of collapse potential in both S3 and S5 samples at optimum dosage of 0.1% whereas, higher dosage recorded increment in collapse. Nano-clay provided greater reduction than other particles due to its higher specific surface area. The reduction in collapse potential was due to increased bond strength between particles by filling of nano-pores with nano-materials. The filling of void spaces also increased the density which was also responsible for reduced collapsibility. Dosage above 0.1% caused agglomeration and formed undesirable void spaces which reduced the density. The higher void spaces allowed entry of more water inside the soil matrix and raised the chance of collapsibility. Changizi and Haddad (2017) performed one dimensional consolidation test on nano-silica treated clay soil sample and observed reduction in settlement of about 63% at optimum dosage of 0.7% nano-silica. Compression index showed reduction after incorporation of nano-silica and minimum value was noticed at optimum dosage of 0.7% whereas, beyond that dosage marginal change was recorded as shown in Fig. 10. The increment in pre consolidation stress was also mentioned and maximised at 0.7% dosage. The improvement in consolidation parameters was due to formation of viscous gel which helped to sustain higher external load with

Table 3 Impact of nano-additives on compaction behaviour of soil

References	Soil type	Nano-material and other additives	Compaction parameters	
			γ_{dmax}	ω_{opt}
Majeed and Taha (2012)	Clayey Silty Sand (Soft soil)	Nano-CuO: 0.5%, 1%Nano-MgO: 0.1%, 0.2, 0.3, 0.4%, Nano-Clay: 0.1, 0.2, 0.3, 0.4%	Increased	Increased
Luo et al. (2012)	Clay	SSA/Cement: (3:1)15% replaced by soilNano-Al_2O_3: 0%, 1%, 2%, 3% by weight of soil	Decreased	Increased
Taha and Taha (2012)	Clayey soil samples with different bentonite contents	Nano-alumina: 0.05, 0.075, 0.1, 0.15, 0.3%Nano-Cu: 0.15, 0.3, 0.5, 0.7% Nano-clay: 0.05, 0.1, 0.15, 0.3, 0.5%	Increased up to optimum dosage and then declined; Nano-clay showed no effect	Decreased up to optimum dosage and then increased
Azzam (2014)	Clay	Polypropylene homopolymer Polymer: 0, 3, 6, 10% by dry wt. of soil	Increased	Decreased
Bahmani et al. (2014)	Residual clay soil	NS: 0, 0.2, 0.4, 0.8, 1% by wt. of soil Cement: 4, 6, 8% by wt. of soil	Decreased	Increased
Khalid et al. (2014)	Kaoline soil	Nano-kaoline: 3% by weight of soil	Increased	Decreased
Majeed et al. (2014)	OL, CH soil types	Nano-Cu: 0, 0.2, 0.4, 0.6, 0.8, 1%Nano-Clay: 0, 0.05, 0.1, 0.2, 0.25, 0.3% Nano-Mg: 0, 0.1, 0.2, 0.3, 0.4%	Increased up to optimum dosage and then declined	Decreased up to optimum dosage and then increased
Zainuddin et al. (2015)	Kaoline soil	Nano-kaolinite: 3% by wt. of clayBentonite and sodium bentonite: 2, 5, 7.5, 10% by wt. of kaolinite	Increased	Decreased
Choobbasti et al. (2015)	Sand	Cement: 5, 9, 14% by wt. of sand Nano-silica: 0, 5, 10, 15% by wt. of sand	Increased up to optimum Nano-content beyond that declined	Decreased up to optimum Nano-content beyond that increased

Table 3 (continued)

References	Soil type	Nano-material and other additives	Compaction parameters	
			γ_{dmax}	ω_{opt}
Jassem and Tabarsa (2015)	CL–ML soil type	Nano-clay: 0, 0.5, 1, 1.5, 2, 2.5% by wt. of soilPPF: 0, 0.3, 0.6, 0.9, 1.2, 1.5%by wt. of soil Fibre length: 6, 12, 18 mm	Decreased	Increased
Moharram et al. (2016)	Clay	Nano-silica and Nano-kaolinite: 0%, 0.5%, 1%, 1.5%. 2%, 2.5%, 3% by dry wt. of soil	Increased up to optimum dosage and then declined	Increased
Changizi and Haddad (2016)	Clay	Nano-silica: 0.5%, 0.7%, 1% by wt. of parent soil	Increased	Increased
Ewa et al. (2016)	Silty clay	Terrasil: 0%, 2%, 4%, 6%, 8%	Increased	Increased
Naseri et al. (2016)	Silty soil	Graphene oxide: 0.02%, 0.05%, 0.1% wt. of cement Cement: 150 kg per cubic meter of soil	Increased	Decreased
Majeed and Taha (2016)	S1-OL, S2-CH type	Nano-Cu: 0%, 0.2%, 0.4%, 0.6%, 0.8%, 1%, 1.2% Nano-Alumina: 0%, 0.1%, 0.2%, 0.3%, 0.4%, 0.5%, 0.6% Nano-MgO: 0%, 0.1%, 0.2%, 0.3%, 0.4%, 0.5%	Increased for both S1 and S2 type	Increased for S1 and Decreased for S2 type
Alsharef et al. (2016)	Clayey sand	Nano-Carbons (CNTs and CNFs): 0.05, 0.075, 0.1, and 0.2% by wt. of soil	Increased	Decreased
Babu and Joseph (2016)	Silty clay	Nano-TiO_2, Nano-fly ash (Both Nano-Materials): 0%, 0.5%, 1%, 2%	Increased	Decreased

Table 3 (continued)

References	Soil type	Nano-material and other additives	Compaction parameters	
			γ_{dmax}	ω_{opt}
Choobbasti and Kutanaei (2017)	Sandy soil	Cement: 6% by dry wt. of soil Nano-silica: 0%, 4%, 8%, 12% by wt. of cement Curing period: 7, 28, 90 days	Increased up to optimum dosage and then reduced	Decreased by cement alone while Increased after adding Nano-silica
Kulkarni and Mandal (2017)	Medium expansive silty soil	FA: 10%, 20%, 30%, 40%, 50% by dry wt. of soilNano-material (Organo siliane based): (1:100), (1:225), (1:400), (1:600) dilution ratio by volume	Increased at higher Nano-content	Decreased
Changizi and Haddad (2017)	Soft clay	Nano-silica: 0.5%, 0.7%, 1%	Increased	Increased
Prabhu et al. (2017)	Clay	Nano-Fly Ash: 10%, 20%, 30% Nano-Cement: 0%, 2%, 4%, 6%, Curing period: 7 Days	Decreased (Nano-sized particles shows higher decrement than non-Nano-sized particles)	Increased (Nano-sized particles shows higher decrement than non-Nano-sized particles)
Onyelowe (2017)	Silty clayey gravel	Nano-structured Waste Paper ash: 3%, 6%, 9%, 12%, 15%Curing time: 7, 14, 28 days	Increased after 6% nano-dosage	Decreased after 6% Nano-dosage
Taha and Alsharef (2017)	Clay	Nano-Carbons (CNTs and CNFs): 0.05, 0.10, 0.20% of dry wt. of soil	Increased up to 0.1% dosage and then declined by both	Decreased by CNTs while CNFs showed no effect
Singh (2017)	Clay	Terrasil: 1%, 1.5%, 2%	Increased	Decreased
Eswaramoorthi et al. (2017)	clay	Nano-Silica: 5%, 10%, 15% Nano-Lime: 2%, 6%, 10% Curing period: 7 days	Decreased	Increased
Tabarsa (2017)	CL–ML type soil	Nano-clay: 0%, 0.5%, 1%, 1.5%, 2%, 2.5%, 3%, 3.5%, 4%	Decreased	Increased

Table 3 (continued)

References	Soil type	Nano-material and other additives	Compaction parameters	
			γ_{dmax}	ω_{opt}
Taha et al. (2018)	CL, CH type soil	Bentonite: 0%, 10%, 20% by dry wt. of soilNano-carbon: 0.05%, 0.075%, 0.10%, 0.20%	Increased (CNFs shows more increased than CNTs)	Decreased (CNFs shows more decreased than CNTs)
Mukri et al. (2018)	Natural Kaoline	Nano-kaoline: 0%, 1%, 2%, 3%	Increased	Decreased
Onyelowe and Duc (2018)	Laterite soil	Cement: 5% NBA: 5%, 10%, 15% Curing period: 14 and 28 days	Increased	Decreased
Hussan and Al-Janabi (2018)	Soft soil	Mix 1: soil + 4% limeMix 2: soil + 4% lime with 0.25%, 0.5%, 1% Nano-CaCo3 as replacement of lime added, Curing period: 7, 14, 28 days	Decreased	Increased
Jahromi and Zahedi (2018)	Clay	Nano-Aluminium: 2%, 4%, 6% by wt. of cement used Cement: 4% and 8% by weight of soil	Decreased by cement while Increased by Nano-dosage	Increased by cement but reduced by Nano-dosage
Shoospasha et al. (2018)	Sandy soil	Cement: 4%, 6%, 8% by dry wt. of sand Nano-silica + cement: 10%, 30%, 50% by dry wt. of sand	Increased by cement alone but after adding Nano-silica leads to reduction	Decreased by Cement alone but Nano-addition leads to increase
Nisha and Roy (2018)	Clay	Nano-silica: 5%, 10%, 15%, 20%, 25%, 30% Bentonite: 10%, 15%, 20%, 25%, 30%, 35%	Decreased	Increased
Baziar et al. (2018)	Kaolinite clay + sand 1:9CS and 1:4CS soil samples prepared for testing	Nano-clay: 1%, 2%, 3%, 4%	Increased up to 3% Nano-clay dosage and then reduced	Slight decreasd
Malik et al. (2019)	Clayey soil	Nano-silica: 5% to 20% by wt. of dry soil	Decreased	Increased

Table 3 (continued)

References	Soil type	Nano-material and other additives	Compaction parameters	
			γ_{dmax}	ω_{opt}
Al-Swaidani et al. (2019)	Expansive clayey soil	Nano-calcined clay: 0%, 1%, 2%, Nano-lime: 0.6%	Reduced by Nano-lime and Increased by Nano-calcined clay	Increased by Nano-lime and reduced by Nano-calcined clay
Ahmadi and Shafiee (2019)	Clayey soil	Nano-silica and micro silica: 0–6%, 28 days curing time	Decreased	Increased
Kirithika and Stalin (2019)	Clayey soil	Nano-Cu slag:1%, 2%, 3%	Decreased	Increased
Kalhor et al. (2019)	Clay	Nano-silica: 0%, 1%, 2%, 3%, 4% Curing period: 42 days	Decreased	Increased
Parsakhoo (2019)	CL, CH	Nano-Silica + Horsetail Ash: 0.5% + 1%, 1% + 2%, 1.5% + 3%, 2% + 4% Curing period: 7, 14, 28 days sample analysis	Increased	Increased
Taha et al. (2019)	Silty clay	Nano-lime and lime: 0.2–1% of dry wt. of soil Curing period: 1, 28, 60 days analysis	Lime: slightly Increased Nano-lime: Increased up to 0.5% dosage and then declined	Lime: Decreased Nano-lime: Decreased up to 0.5% dosage and then declined
Tanzadeh et al. (2019)	Clayey soil	Lime: 2%, 4%, 8%, 16% Nano-lime: 0.5%, 1%, 2%, 4%	1-day curing: Decreased Higher Curing: Increased	1-day curimg: Increased Higher curing: Decreased
Zainuddin et al. (2019)	Bentonite soil	Nano-bentonite: 0%, 1%, 2%, 3%	Increased	Decreased
Safarzadeh et al. (2019)	Clay and silt	Nano-clay: 0%, 0.5%, 1%, 1.5%, 2% Curing period: 7 days	Increased	Decreased
Tomar et al. (2019)	Clayey soil	Nano-silica: 1%, 3%, 5%, 7% PPF: 0.1%, 0.4%, 0.7%, 1%, 1.3%	Decreased	Increased

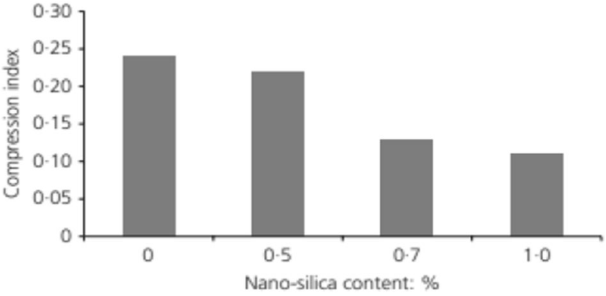
Table 3 (continued)

References	Soil type	Nano-material and other additives	Compaction parameters	
			γ_{dmax}	ω_{opt}
Sarli et al. (2020)	Loess soil	Nano-Sio2, Recycled polyster fibre:2%, 4% and 6% by weight of soil in proportion of 33% and 50% for mixture	Decreased	Increased
Sobhani Nezhad et al. (2020)	Gas oil contaminated clayey soil	Nano-silica and hydrated lime: 1%, 2% and 3% (mutually and individually both)	Decreased	Increased
Yousefi et al. (2020)	Clay	Nano-cement and cement: 1, 2, 3 and 4% by dry weight of soil	Decreased	Increased
Bhadra and Leander (2020)	Clayey soil	Nano-calcium silicate: 0.2, 0.4, 0.6, 0.8, 1.0% and Lime: 2, 4, 6, 8% by weight of soil	Lime: Increased up to 6% dosage and then declined Nano-Calcium silicate: Decreased up to 0.4% and then increased	Lime: Increased Nano-calcium silicate: Increased
Zahoor and Jassal (2020)	Alluvial soil	Terrasil and Zycobond:0.6, 0.9 and 1.3 kg/m3	Increased up to 0.9dosage and then declined	Increased up to 0.9 dosage and then declined
Karumanchi et al. (2020)	Soft clay soil	Nano-clay: 0.1, 0.2, 0.3, 0.4 and 0.5% by weight of soil	Increased up to 0.15% dose and then reduced	Decreased consistently up to 0.5% dose
Bhadra and Leander (2020)	Clay	Lime: 2, 4, 6, 8% Nano-Calcium Silicate: 0.2%, 0.4, 0.6, 0.8, 1%	Reduced at 0.2% Nano-dose and then Increased at higher dosages Optimum dose: lime (6%) with Nano-Calcium silicate	Increased
Ghavami et al. (2021)	Clay	Nano-Silica: (0.5–2%) Silica fume: (5–20%), Cement kiln dust:15%	Silica fume reduced MDD where Marginal reduction seen with Nano-silica	Increased by Silica fume and marginally increased by Nano-silica

Table 3 (continued)

References	Soil type	Nano-material and other additives	Compaction parameters	
			γ_{dmax}	ω_{opt}
Bargi et al. (2021)	Clayey sand	Nano-silica (8 nm and 15 nm): 0.25%, 0.5% and 0.75% Silica fume (600 nm): 0.25%, 0.5% and 0.75%, Cement	Decreased	Increased
Mir and Reddy (2021)	Silt	Nano-alumina: 0.5, 1.0, 1.5, and 2.0%	Increased up to 1.5% dose	Decreased
Al-Swaidani and Meziab (2021)	Clay and silt	Nano-lime: 0.6%, Nano-natural pozzolana: 0%, 1% and 2%	Nano-lime showed no changes whereas Nano-natural pozzolona increased	Reduced by nano-pozzolona and no changes observed by nano-lime
Li et al. (2021)	Loess soil	G.O: 0.03, 0.06, 0.09, 0.12 wt. %, cement: 15% by wt. of soil	Increased	Decreased
Kalhor et al. (2022)	clay	Nano-silica:1–4% by wt. of soil	Decreased	Increased
Kannan et al. (2022)	Low plastic organic soil	Nano-calcium carbonate: 0.2–0.8% by wt. of soil	Marginally Decreased	Decreased

Fig. 10 Effect of nano-silica content on compression index of clay (Changizi & Haddad, 2017)



less deformation. The effective improvement of clay was experienced up to 0.7% dosage beyond that less prominent change was noticed.

Ahmadi (2019) examined the confined stiffness factor of nano-treated cemented fine sand with one dimensional settlement analysis. Sand was incorporated with nano-alumina, nano-silica and nano-magnesium oxide with dosages as 0.4%, 0.8% and 1.2% individually along with cement (4% and 6%). The stiffness factor of amended sand increased up to 0.8% nano-content beyond that marginal increment was reported with all the three types of additives. The higher stiffness factor was received in nano-alumina treated sand than other two nano-additives whereas, minimum gain was obtained with nano-magnesium oxide. Nano-alumina at 0.8% dosage alone increased the constrained young's modulus by 15% whereas with 6% cement increment was uplifted to 23%. The higher pozzolanic ability of nano-materials led to the formation of additional calcium silicate hydrate gel after reaction with calcium hydroxide and increased the paste stiffness. Al-Obaidi et al. (2020) observed reduction in collapse potential in gyspeous soil (poorly graded sand) after treatment with nano-silica fume and silica fume. The reduction of 50–80% was reported with both sized additives. High collapsible soil was transformed to moderate or slightly collapsible soil at 3% nano-silica fume content; whereas 10% silica dosage was required to obtain such behaviour. This was attributed to the higher specific surface area of nano-material than micro material. The dissolution of particles was prevented by the nano-additive due to improved adhesion and enclosed particles together which resist the water entrance. In a same way, Haeri and Valishzadeh (2020) depicted partial improvement in collapse of loess soil (ML) treated with nano-silica, nano-clay and nano-calcium carbonate. The maximum reduction in settlement or collapse was obtained with nano-calcium carbonate and minimum with nano-clay. Settlement was reduced by 48.6%, 54.3% and 60% after incorporation of nano-clay, nano-silica and nano-calcium carbonate, respectively. Nano-materials improved the inter particle bonding strength and impart more aggregated particles. The Saturated un-stabilised soil experienced breakage of matric suction and weakening of bond which was responsible for collapse whereas, stabilised saturated soil experienced less destruction of bond and matric suction. Mahmoudian et al. (2020) compared the influence of nano- (70 nm) and micro- (685 nm) alumina particles on collapsibility of three types of collapsible soil samples named as S1, S2 and S3 which were classified as CL–ML for all three types with different minor variation in plasticity characteristics. Compaction technique was applied which reduced the collapsibility from severe to moderate due to deprived porosity and denser soil matrix. Nano- and micro-alumina was added as 0.5–1.5% by weight of soil. Optimum dosage was 1% at which minimum collapse potential was recorded whereas, 1.5% dosage imparted increment in collapsibility. Higher dosage above optimum resulted to agglomeration phenomenon and increased the collapsibility due to decreased point contacts between the particles. Nano-alumina resulted higher reduction in collapse than micro-alumina. Nano-treatment modified the trend from moderate to slightly collapsible. Collapsibility of S1 soil was reduced by 6 and 4 times than untreated soil at optimum dosage of nano- and micro-alumina, respectively. Nano-alumina reduced the collapse of S2 and S3 by 4 and 2.75 times whereas micro sized alumina imparted reduction of 3 and 2.2 times respectively.

2.3.2 Nano-clay

Cheng et al. (2020) modified the consolidation characteristics of clay after incorporation of nano-bentonite as 0.5–2% by weight of soil. Nano-bentonite reduced the void ratio and compression coefficient. The coefficient of consolidation was lower up to 1% dosage of nano-bentonite and higher at 2% as compared to pure soil. The addition of nano-bentonite altered the soil microstructure by filling of void spaces which improved the cohesiveness and counteract the compressibility. The compression coefficient was majorly influenced at low pressure due to availability of void spaces where high pressure provide less void ratio with more compact soil matrix. Karumanchi et al. (2020) investigated the settlement parameters of soft clay soil intermixed with nano-clay. Nano-clay was incorporated as 0.1–0.5% and optimum dosage mentioned was 0.15% at which minimum final settlement was recorded after curing. The reduction in coefficient of consolidation was also mentioned at the optimum dosage of nano-clay. The improved parameters were mainly due to filling of pore spaces by nano-clay particles. Johari et al. (2021) modified the collapsible behaviour of highly collapsible soil classified as low compressible silt with the help of nano-clay. Soil collapsibility was reduced after incorporation of 5% nano-clay which was mentioned as optimum dosage in wet mixing sample preparation. A significant reduction in collapsible strains was obtained in wet method of mixing as compared to dry method. Montmorillonite mineral of nano-clay enhanced the vanderwall and electrostatic forces between particles which improved the adhesiveness. The denser structure was obtained with more frictional interlock and adhesion between particles.

2.3.3 Other nano-additives

Azzam (2014) influenced the consolidation characteristics of clay with polymer stabilisation (3–10%). The size of nano-composites formed was in proportion to its dosage and modified the compression and recompression index of soil. The reduction in consolidation parameters and void ratio was reported as the size of nano-composites increased. Formation of nano-composites was attributed to the ion exchange phenomenon which altered the microstructure of the clay by filling of voids. Altered microstructure resulted in reduced void ratio and consolidation settlements. Void ratio was reduced up to 36% at 10% polymer content where settlement was decreased up to 11% and 38% at low and upper limit of polymer dosage. Babu and Joseph (2016) mixed nano-fly ash and nano-titanium dioxide in silty clay and determined the optimum dosages for both the additives. Consolidation settlement was decreased by 67% and 60% in soil treated with nano-fly ash (1%) and nano-titanium dioxide (0.5%), respectively. The influence on settlement reduction by nano-fly ash was more than nano-titanium dioxide.

Mahmood et al. (2021) influenced the consolidation properties of soft clay with the help of graphene oxide. The reduction in void ratio, coefficient of consolidation and coefficient of volume compressibility was stated after incorporation of 0.1% graphene oxide content.

Garphene oxide acted as a binding material and filled the blank spaces between the particles. The smaller particles blocked the pore spaces and reduced the rate of flow of water which decreased the consolidation coefficient. The absorption of confined free water by particles of graphene oxide took place and reduced the compressibility.

On the basis of studied literature, reduction in consolidation parameters was observed in nano-amended soils as compared to natural. The nanoparticles effectively reduced the void ratio by filling of both nano- and micro-void spaces between the soil particles. The reduction in void spaces was also responsible for decrement in settlement of the soil. The coefficient of consolidation and compression index of treated soil was found to reduce with the increase in dosage up to optimum. Beyond that marginal or inverse behaviour was noticed due to agglomeration of particles. The agglomeration effect was responsible for formation of unwanted unstable lumps which increased the void ratio and reduced the density and invited more water in the soil matrix. The reduction in compression index is an indicative parameter for decrease in compressibility of the soil. The treated collapsible soil experienced reduction in collapse potential due to increase in density of the soil by filling of void spaces and decrease the plasticity characteristics. The effect of the nano-additives alone and with other admixtures on consolidation parameters soil is presented in tabular form in Table 4.

2.4 Permeability

Hydraulic conductivity is the key factor which is required in designing of clay liners in structures such as water storage structures, lining of canals, tunnels, solid waste disposal sites etc. which faces problem related to seepage. Permeability characteristics depend on the type of soil structure and other geotechnical properties of soil such as void ratio, density, particle size etc. The impact of permeability (hydraulic conductivity) on weak and soft soils after amendment with the nanoparticles based on the available past studies is presented in this section.

2.4.1 Nano-silica and nano-silane-based compound

Bahmani et al. (2014) examined the impact of nano-silica (0.2–1%) and cement (4–8%) on residual soil classified as CL. Nano-silica with two particle sizes such as 15 nm and 80 nm were utilised. The reduction in permeability reduced up to 0.4% nano-silica content beyond that increment was noticed as shown in Fig. 11. Maximum reduction was attained after addition of 0.4% nano-silica with 8% cement. Nano-silica eliminated the small and large sized pores by C–S–G gel. The higher packing density was provided by 15 nm sized nano-silica than 80 nm due to higher specific surface area of 15 nm particle size. Kirithika et al. (2015) compared the influence of nano-sized and non-nano-sized silica (5%) and lime (10%) particles on hydraulic conductivity of highly compressible clay. Permeability was reduced by both sized additives but greater reduction was provided by the nano-sized silica and lime particles. Nano-sized particles effective filled the void spaces between the soil particles due to their higher fineness and thus provided less permeable clay matrix. The similar study was also performed by Eswaramoorthi et al. (2017) in which comparison of both nano-sized and non-nano-sized silica, lime particles was investigated to modify the permeability of clay. Higher rate of reduced permeability was recorded with nano-sized silica particle than non-nano-silica particles. Vadivel and Stalin (2015) prepared the nano-silica-treated cementitious grout for groun modification and analysed its hydraulic

Table 4 Impact of nano-additives on consolidation parameters of soil

References	Soil type	Nano-materials and other additives	Consolidation parameters				
			C_c	C_v	C_r	Settlement	Collapse potential
Azzam (2014)	Clay	Polypropylene homopolymer: 0, 3, 6, 10% by dry wt. of Soil	Reduced	–	Reduced	Reduced	–
Babu and Joseph (2016)	Silty Clay	Nano-fly ash and Nano-TiO_2 (Both Nano-Materials): 0%, 0.5%,1%,2%	–	–	–	Reduced more by Nano-fly ash than Nano-TiO_2	–
Iranpour and Haddad (2016)	Silty Clay	Nano-Clay, Nano-Silica, Nano-Alumina, Nano-Copper: 0.1%, 0.2%, 0.4%, and 0.6%	–	–	–	–	Reduced more by Nano-Clay at 0.1% dose
Changizi and Haddad (2017)	Soft Clay	Nano-Silica: 0.5%, 0.7%, 1%	Reduced	–	–	Maximum Reduced at 0.7%	–
Tabarsa (2017)	CL–ML	Nano-Clay: 0%, 0.5%, 1%, 1.5%, 2%, 2.5%, 3%, 3.5%, 4%	–	–	–	–	Reduced
Ahmadi (2019)	Sand	Nano-Silica, Nano-Aluminium oxide, Nano-Mgo: 0.4%, 0.8% and 1.2% for all OPC: 3%, 6%	–	–	–	Reduced more by Nano-Alumina along with cement, least reduction showed by Nano-MgO	Reduced
Cheng et al. (2020)	Clayey Soil	Nano-Bentonite: 0.5%, 1%, 1.5%, 2%	–	Increased	–	Increased	–
Al-Obaidi et al. (2020)	Poorly graded Sand	Nano-Silica fume (NSF): 1, 2, 3, 4, 5% and Silica Fume: 5, 10, 15, 20, 25%	–	–	–	–	Reduced by both the additives but more influenced by NSF at 3% dose

Table 4 (continued)

References	Soil type	Nano-materials and other additives	Consolidation parameters				
			C_c	C_v	C_r	Settlement	Collapse potential
Haeri and Valishzadeh (2020)	Loess Soil	Nano-Silica, Nano-Clay, Nano-calcium carbonate: 0.1, 0.2 and 0.4% for all	–	–	–	–	Reduced by all the additives, maximum Reduced by 60% with Nano-calcium carbonate
Karumanchi et al. (2020)	Soft Clay Soil	Nano-Clay: 0.1, 0.2, 0.3, 0.4, 0.5%	–	Increased with the curing period at 0.15% optimum dosage	–	Decreased as the curing period increases, optimum dose was 0.15%	–
Mahmoudian et al. (2020)	Collapsible loess Soil (CL–ML)	Nano-Alumina(70 nm): 0.5, 1, 1.5% Micro Alumina: 0.5, 1, 1.5%	–	–	–		Reduced to minimum at 1% dose and then Increased
Johari et al. (2021)	Collapsible Soil (ML)	Nano-Clay: 1, 3, 5, 10,15,20%	–	–	–	–	Decreased more with wet mixing method than dry
Mahmood et al. (2021)	Soft Clay	Graphene oxide: 0.1%	–	Reduced	Reduced	Reduced	–
Kannan et al. (2022)	Low plastic organic Soil (OL)	Nano-calcium carbonate: 0.2–0.8% by wt. of Soil	Reduced	Increased	Reduced	–	–

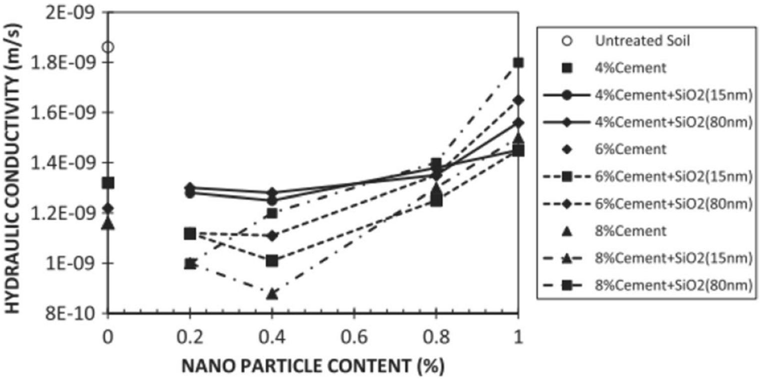


Fig. 11 influence of nano-silica on hydraulic conductivity of clay (Bahmani et al., 2014)

performance. The nano-treated grout showed greater impermeability as compared to neat cement grout. The maximum reduction in permeability was observed at 1.5% nano-content at water cement ratio of 1.20. The stronger bonding between the particles was noticed due to reaction of nano-silica and cement hydration products which formed crystallised gel in the form of *C–S–H* and thus reduced the permeability potential.

Kulkarni and Mandal (2017) performed falling head permeability test to determine the influence of fly ash and nano-material (organo silnane-based compound) on weak silty clay. Soil was incorporated with dilution ratios of nano-material as (1:100), (1:225), (1:400) and (1:600) along with 10–50% replacement of soil with fly ash. The inclusion of additives reduced the permeability. The maximum decrement of 99.90% was recorded at dilution ratio of 1:225 with 30% fly ash. The behaviour of reduced permeability potential was attributed to the formation of strong chain of siloxane bonds (*Si–O–Si*) which impart water repellent property to the soil surface and thus provide hydrophobicity. The exchange of cations promoted the conversion of silanol to siloxane bonds and these bonds neutralised the negative charge of clay which improved the attraction between particles. Nano-material and fly ash provided the sufficient amount of silica to form these stronger chains of bonds. These siloxne bonds increased the density and make soil impermeable. Kakavand and Dabiri (2018) improvised the permeability of silty sand mixture with the help of colloidal nano-silica with concentration of 5%. Sand was admixed with 5%, 10% and 15% of silt. Colloidal nano-silica and silt fines reduced the drainage conditions which decreased the permeability and reduced the chances of liquefaction in sand. A decline of 58% was received after treatment of sand with colloidal silica and silt fines. The decrement in permeability was proportion to the percentage of silt fines in both dry and nano-treated sand. Nisha and Roy (2018) added nano-silica (5–25%) and bentonite (10–35%) in clay to modify the permeability parameters. The permeability of treated clay was reduced due to more water absorption capacity of nano-silica and higher specific surface area. The absorbed water filled the pores and decreased the porosity which ultimately declined the permeability.

Kulanthaivel et al. (2020) incorporated nano-silica and white cement in clay both individually (7% each) and mutually (2% nano-silica + 3% White Cement). Nano-silica alone provided greater reduction in permeability than white cement. The maximum decrement was observed at 2% nano-silica mixed with 3% white cement in soil. The treated soil experienced 45% reduction in permeability. The tiny size of nano-silica helped it to permeate easily into the pores and modify the structure. The permeating ability of nano-silica inside the soil matrix was mentioned higher than other conventional materials such as lime, cement etc., whereas it lags in the cementitious property. Bargi et al. (2021) inspected the influence of nano-silica with 15 nm particle size termed as nano-silica 200 (0.25%, 0.5% and 0.75%) on cemented (7%) clayey sand along with different types of fine content such as silt, kaolinite and bentonite. Soil with bentonite fine content experienced higher reduction in permeability than kaolinite and silt. The higher silica content of bentonite increased the pozzolanic reactions and led to higher growth of binding gel. The lesser size of bentonite than kaolinite and silt occupied higher number of voids and provided more impermeable soil. The comparison between nano-silica (8, 15 nm) and silica fume on cemented sand was also studied. Nano-silica with 8 nm size provided greater reduction than 15 nm size and silica fume due to its higher specific surface area. Nano-silica (both sized) imparted significant reduction up to 0.5%. Beyond that less prominent change was recorded where silica fume continuously reduced the permeability up to 0.75% dosage. Nano-silica experienced agglomeration effect beyond 0.5% dosage where no such impact was noticed with silica fume. The reduction in permeability was attributed to the higher silica content of additives which upgraded the pozzolanic reactions and formed more binding material. The binding material filled the void spaces and decreased the permeability.

2.4.2 Nano-copper, nano-alumina and nano-lime

Luo et al. (2012) analysed that hydraulic conductivity of cohesive soil treated with SSA/Cement (15%) and nano-alumina (1–3%). At initial curing up to 7 days, higher permeability was observed than untreated soil, whereas after 14 days, lower conductivity was reported. SSA and cement formed hydration products like calcium hydroxide and C–S–H gel which occupied the pore spaces. The curing played a vital role in the formation of such hydration products by providing sufficient interval for hydration reactions. The addition of nano-alumina to the treated soil resulted in higher permeability due to formation of gel structure. Taha and Taha (2012) reported no change in hydraulic conductivity in low bentonite content soil samples such as S1 (CL) and S2 (CL) after addition of nano-copper and nano-alumina as additives. The soil with higher bentonite content such as S3 (CH) and S4 (CH) experienced reduction in conductivity after treatment.

Ng and Coo (2014) incorporated both nano-copper and nano-alumina individually in clay to modify permeability characteristics. The prominent reduction in hydraulic conductivity was observed at 2% dosages beyond that less significant reduction was noticed. A reduction of 45% and 35% was attained with nano-copper and nano-alumina. The clogging of soil pores by nano-additives was observed which was responsible for this behaviour. The larger particle size of nano-copper than nano-alumina was attributed as the reason for better performance of nano-copper. Taha and Taha (2016) performed hydraulic conductivity test on four different types of clay samples with variation of bentonite contents such as S1 (nill bentonite), S2 (5% bentonite), S3 (10% bentonite) and S4 (20% bentonite). Samples were treated with nano-alumina and nano-copper particles with dosages of 0.05–0.3% and 0.15–0.7% respectively. Soil sample without bentonite (S1) experienced insignificant reduction in conductivity whereas S2, S3 and S4 samples recorded notable reduction after treatment with nano-copper and nano-alumina individually. This behaviour was probably due to clogging of voids in higher bentonite content samples. Nanoparticles overlapped between the particles and filled up the void spaces. Nanoparticles possessed higher particle density which resulted to higher maximum dry density and reduced the pore spaces. The positive charge of nano-material and negative charge of clay particles resulted attraction and provided denser clay matrix. The effect of drying cycles was also inspected on the treated soil samples. Hydraulic conductivity was increased after 1–2 cycles due to formation of cracks. Nano-alumina with low bentonite content samples imparted no change which may be due to low dosage, where notable increment was reported with nano-copper due to formation of continuous voids at high bentonite content (S3 and S4). Nano-alumina and nano-copper reduced the increment rate of hydraulic conductivity by 5 and 7 times, respectively compared to untreated soil samples. More effective modification by nano-additives was observed in higher bentonite content samples.

Prabhu et al. (2017) compared the hydraulic conductivity of nano-sized and non-nano-sized lime-fly ash treated clay. Clay was amended with 10% fly ash and 10% lime mutually for both the sized additives. Both size of additives reduced the coefficient of permeability but reduction with nano-sized fly ash treated clay was more than non-nano-fly ash sized particles. This behaviour may be attributed to the higher fineness of Nano-sized particles, 10 times higher reduction was reported on comparison with non-nano-sized fly ash additives. Kannan et al. (2022) investigated the impact of nano-calcium carbonate on low plastic organic soil with the variation in dosage from 0.2 to 0.8% by weight of soil. The coefficient was found to increase up to 0.4% dosage whereas it was decreased at higher dosages. The least value was recorded with 0.8% treatment which was still on higher side when compared to untreated soil. The flocculation of the soil particles was the major cause for permeability increment up to 0.4% dosage whereas higher dosage experienced formation of cementitious gels which led to pore reduction. The exponential reduction in the Kv value was mentioned after curing of 90 days.

2.4.3 Nano-clay and other nano-soil particles

Khalid et al. (2014) found reduction of 56% in hydraulic conductivity of kaolin soil after addition of nano-kaolin (3%). This behaviour was attributed to the clogging of nano- and micro-pores by nano-kaolin which reduced the porosity. Structure of soil was disrupted by dispersion of positively and negatively charged nano-soil particles. The similar study by Mukri et al. (2018) investigated the impact of nano-kaoline on Kaoline soil. A consistent reduction in hydraulic conductivity was seen as the dosage of nano-kaoline increased from 1 to 3% by weight of soil. Nanoparticles filled the void spaces which was in micron sizes and clogged the pores of natural soil.

Zainuddin et al. (2015) estimated the hydraulic conductivity of kaoline soil treated by Nano kaolinite (3% by weight of soil) based on the graphs of hydraulic conductivity in the compaction plane. The treated soil showed less permeability than natural. Salemi et al. (2016) modified the hydraulic permeability characteristics of Geo synthetic clay liner by partial replacement of bentonite with nano-clay particles with dosages from 10 to 20%. Nano-clay treated bentonite showed maximum reduction at 15% dosage beyond that increase in conductivity reduction was noticed at 20% dosage. This behaviour was attributed to the improved packing density of the bentonite by pore filling due to very tiny scale of nano-clay. Higher swelling potential of nano clay also reduced the pore spaces. The flow of water was prevented by higher water absorption and cation exchange capacity of nano-clay. The increase in rate of permeability at higher dosages was due to agglomeration. Baziar et al. (2018) modified the permeability characteristics of core material of earthen dam. Sand was admixed with 10% (1:9CS) and 25% (1:25CS) kaoline clay along with nano-clay dosages of 1–4%. Nano-clay and kaoline clay efficiently reduced the permeability to meet the desirable conditions by filling the pore spaces in sand. Nano-clay acted as a filler material due to higher specific surface area and reduced the porosity. Sand with 25% clay (1:25CS) experienced higher decrement than 10% sand mixed with clay (1:9CS). The inclusion of nano-clay decreased the permeability up to 3% dosage beyond that increment was recorded due to agglomeration which increased the unwanted ratio of voids. The impact of nano-clay was than clay due to its higher specific surface area. The method of mixing of nano-clay in soil played a vital role in reduction of permeability. The ball mixing method was superior to manual mixing as it provided better dispersion of nano-clay in the soil matrix.

Zainuddin et al. (2019) evaluated the permeability characteristics of bentonite mixed with nano-bentonite at dosages as 1–3%. The pores inside the soil structure were clogged by Nano bentonite and resulted in reduction of hydraulic conductivity. The dispersion of positive and negative charges disrupted the microstructure of the soil. Similarly, Cheng et al. (2020) examined the permeability coefficient of clay stabilised with nano-bentonite (0.5–2%). On comparison with pure soil, dosage up to 1.5% of nano-bentonite displayed lower coefficient. The higher coefficient was recorded at 2% dosage. Lower consolidation pressure provided effective reduction in coefficient of permeability and constant trend was reported on application of higher pressure. At higher pressure of consolidation, nano-bentonite changed the soil skeleton by formation of new cementitious compounds which provided new drainage paths to discharge water. Nano-bentonite helped to reduce the size and shape of void spaces and thus reduced the coefficient of permeability as the dosage of nano-bentonite increased up to 1.5%. Karumanchi et al. (2020) stated nill permeability characteristics in nano-clay-treated soft clay due to filled void spaces by nano-material at nano-scale level. Amin et al. (2020) experienced maximum reduction of 21.76% in hydraulic conductivity of sandy soil treated with nano-sandy soil particles at dosage of 4%. The soil was mixed with dosages of nano-soil as 1–4% by weight of soil. A slight decrement was recorded after 1% dosage of nano-soil.

2.4.4 Other nano-additives

Azzam, (2014) modified the clay microstructure with the polymer stabilisation. Polymer was admixed with the dosages such as 3–10%. At 10% dosage, voids were almost filled with nano-composites and reduced the conductivity. Permeability reduction was found proportional to the size of nano-composites. Johnson and Rangaswamy (2015) documented drastic decrease in permeability of nano-chemical (terrasil) treated clay soil. The reduction was in proportion to dosage of terrasil. Soil became water proof by permanent siliconisation of the soil's surface due to chemical reaction. Reginatto et al. (2016) studied the hydraulic conductivity performance of residual clayey soil under the influence of iron nanoparticle in colloidal form. No significant change in the natural conductivity was noticed with lower concentration (1 g/l and 4 g/l) of nano-iron whereas prominent reduction with higher concentration (7 g/l and 10 g/l) was reported. The clogging of pores in the soil matrix due to formation of clusters was responsible for reduced permeability at higher concentrations.

Alsharef et al. (2016) incorporated multi-walled carbon nano-tubes (MWCNTs) and carbon nano-fibres (CNFs) in weak soil classified as clayey sand with dosages from 0.05 to 0.2%. Both types of nano-carbons reduced the permeability whereas effective decrement was given by CNFs as compared to MWCNTs. The prominent reduction was observed between 0.05 and 0.1% of dosage beyond that less significant reduction was reported. The porosity of the treated soil matrix was decreased by the nano-additives which was responsible for reduced permeability. Similarly, Taha and Alsharef (2017) improved the permeability of low compressible clay with the inclusion of nano-carbons (CNTs and CNFs). Nano-carbons provided sufficient reduction in permeability to fulfil the criteria as a landfill barrier. The reduction was consistent and proportional to the dosage of nano-carbons (0.05–0.2%). Treated soil experienced less crack intensity factor due to lower swelling and shrinkage potential which caused decrement in conductivity. CNFs provide better reduction than CNTs which may be due to its larger aspect ratio in dimensions.

From the review of literature, it can be concluded that the inclusion of nanoparticles led to reduction in permeability characteristics soil. The finer particles of nano-additives filled the pore spaces and clogged the space essential for the flow of water. The higher specific surface area of particle provides greater dispersion of additives in a more uniform and homogeneous way. The hydration reactions between nanoparticles and soil leads to the formation of cementitious gel type compounds which occupied the void spaces and reduced the inter particle spacing. The effect of the nano-additives alone and with other admixtures on permeability of soil is presented in tabular form in Table 5.

2.5 Swelling and shrinkage

This section of the article deals with the swelling and shrinkage behaviour of nano-treated clays and sands. Some clays such as bentonite or black cotton soil contains higher amount of montmorillonite mineral which is responsible for higher swelling and shrinkage strain. This kind of behaviour of soil resulted to uneven settlement of soil present below the structures and increases the chances of structural damage. The influence of nano-additives with and without conventional additives on the swelling and shrinkage behaviour of soils reported by various researchers has been discussed. Suitable comments are stated based on the results of previously performed swelling and shrinkage test.

2.5.1 Nano-copper, nano-alumina and nano-lime

Luo et al. (2012) observed effective reduction in volumetric swelling after replacement of soil with SSA/Cement (15%) in 3:1 and nano-alumina (1–2%). Maximum reduction in volumetric swelling was reported at 1% nano-alumina dosage with 15% SSA/Cement due to attainment of least plasticity index. Formation of *C–S–H* gel as a hydration product helped in binding of soil particles and restricts the swelling potential. Taha and Taha (2012) examined four types of nano-stabilised expansive clayey soil categorised on the basis of varied bentonite content in soil as 5%, 10% and 20% and termed as S1, S2, S3 and S4, respectively. Nano-clay showed no improvement in volumetric strain due to higher expansive nature. Nano-alumina and nano-copper reduced the expansive and shrinkage strain up to the certain dosages and then increment was recorded. The reduction in strain was attributed to the increase in density and decreased plasticity of the soil. Higher dosages experienced agglomeration of the particles which caused reduction in the density due to increased void ratio and thus provide higher volumetric strains. Significant strain reduction was recorded with nano-copper treated soil than nano-alumina due to higher particle density of nano-copper.

Taha and Taha (2016) utilised the zeta potential values to indicate the swelling potential of four different clay samples with varied bentonite contents such as S1 (0% bentonite), S2

Table 5 Impact of nano-additives on hydraulic conductivity of soil

References	Soil type	Nano-materials and other additives	Permeability (K)
Luo et al. (2012)	Cohesive Soil	SSA/Cement: (3:1)15% replaced by SoilNano-Al_2O_3: 0%, 1, 2, 3%	Reduced by SSA/cement and Increased by Nano-Alumina
Taha and Taha (2012)	Clayey Soil samples with different bentonite contents S1 (0%), S2 (5%), S3 (10%) and S4 (20%)	Nano-Alumina: 0.05, 0.075, 0.1, 0.15, 0.3%Nano-Cu: 0.15, 0.3, 0.5, 0.7% Nano-Clay: 0.05, 0.1, 0.15, 0.3, 0.5%	No changes in lower bentonite content Soil while prominent reduction in higher bentonite content soil samples attained with additives
Bahmani et al. (2014)	Clay	Nano-Silica: 0, 0.2, 0.4, 0.8, 1% by wt. of Soil Cement: 4, 6, 8% by wt. of Soil	Reduced (least observed at 0.4% Nano-Silica)
Khalid et al. (2014)	Kaoline Soil	Nano-Kaoline: 3% by weight of Soil	Reduced
Ng and Coo (2014)	Clay	Nano-CuO: 2, 4, 6% by wt. of Soil Nano-Al_2O_3: 2, 4, 6% by wt. of Soil	Reduced up to 2% dose beyond that less significant results are received, Reduced by 30% and 45% after Nano-Alumina and Nano-Copper treatment respectively
Zainuddin et al. (2015)	Kaoline Clay	Nano-kaolinite: 3% by wt. of ClayBentonite and sodium bentonite: 2, 5, 7.5, 10% by wt. of kaolinite	50% reduction
Zahedi et al. (2014)	Clay	Nano-Clay: 0, 1.5, 3, 4.5, 6%	Decreased
Kirithika et al. (2015)	Clay	Nano-Silica: 5%Nano-Lime: 10% by wt. of Soil	Reduced by 10 times than untreated Soil
Johnson and Rangaswamy (2015)	Soft Clay	Cement: 1, 2, 3, 4, 5% by wt. of Soil Terrasil: 0.03, 0.05, 0.07, 0.09% by wt. of Soil	Reduced
Vadivel and Stalin (2015)	Cement content Sand grout	Nano-Silica: 0%, 0.1%, 0.5%, 1%, 1.5% to cement content Sand grout	Decreased
Reginatto et al. (2016)	Clay	Nano-iron: 1 g/l, 4 g/l, 7 g/l, 10 g/l	Reduction observed when dose was more than 4 g/l dose
Salemi et al. (2016)	Bentonite Soil in GCL	Nano-Clay: 0%, 10%, 15%, 20% of bentonite content	Decreased up to 15% dose beyond that Increased
Alsharef et al. (2016)	Clayey Sand	Nano-Carbons (CNFs and CNTs): 0.05, 0.075, 0.1, and 0.2% by wt. of Soil	Reduced (more by CNFs than CNTs)

Table 5 (continued)

References	Soil type	Nano-materials and other additives	Permeability (K)
Kulkarni and Mandal (2017)	Silty Clay Soil	Fly Ash: 10%, 20%, 30%, 40%, 50% by dry wt. of SoilNano-material: (1:100), (1:225), (1:400), (1:600) dilution ratio by volume	Maximum Decreased at optimum dose of 1:100 Nano-+30% fly ash (99.89% reduction observed)
Prabhu et al. (2017)	Clay	Nano-Fly Ash: 10%, 20%, 30% Nano-Cement: 0%, 2%, 4%, 6%, 8%, 10% Curing period: 7 Days	Reduced (10 times more reduction than Non-Nano-size of same additives)
Taha and Alsharef (2017)	CL	Nano-carbons: 0.05, 0.075, 0.1, 0.2%	Reduced more by CNFs than CNTs (3 times maximum reduction)
Eswaramoorthi et al. (2017)	Clay	Nano-Silica: 5%, 10%, 15% Nano-Lime: 2%, 6%, 10%	Reduced 10 time more by Nano-sized than Non-Nano-size additives
Mukri et al. (2018)	Natural Kaoline	Nano-kaoline: 0%, 1%, 2%, 3%	Reduced
Kakavand and Dabiri (2018)	Sand-Silt mixture	Colloidal Nano-Silica: 5, 10, 15%	58% declined
Baziar et al. (2018)	Kaoline Clay in Sand in proportion of 1:9 and 1:4	Nano-Clay: 1%, 2%, 3%, 4%	Both Soil samples showed reduction, maximum Reduced at 3% and then rises (1:4 shows more reduction
Nisha and Roy (2018)	Clay	Nano-Silica: 5%, 10%, 15%, 20%, 25%, 30% Bentonite: 10%, 15%, 20%, 25%, 30%, 35%	Reduced
Zainuddin et al. (2019)	Bentonite	Nano-bentonite: 0%, 1%, 2%, 3%	Decreased
Kulanthaivel et al. (2020)	Clayey Soil	Nano-Silica: 3%, 5%, 7%, 9% White cement: 1%, 2%, 3%, 4%	Reduced
Cheng et al. (2020)	Clayey Soil	Nano-Bentonite: 0.5%, 1%, 1.5%, 2%	Reduced
Qasaimeh et al. (2020)	Clay	Nano-Bentonite: .0.1, 0.2, 0.4, 0.6, 0.8, 1, 1.2%	Reduced
Karumanchi et al. (2020)	Soft Clay	Nano-Clay: 0.1, 0.2, 0.3, 0.4 and 0.5%	Reduced to nill
Amin et al. (2020)	Sandy Soil	Nano-Sandy Soil:1%, 2%, 3% and 4%	Maximum reduction of 21.76% at 4% dosage

Table 5 (continued)

References	Soil type	Nano-materials and other additives	Permeability (K)
Bargi et al. (2021)	Clayey Sand (SC) with silt, kaolinite and bentonite fines	Nano-Silica (8 and 15 nm): 0.25%, 0.5% and 0.75% Cement: 7% Silica fume: 0.25–0.75%	Reduced more by Nano-Silica with 8 nm sized than 15 nm sized Nano-Silica, bentonite fines showed more reduction than others
Kannan et al. (2022)	Low plastic organic Soil (OL)	Nano-calcium carbonate: 0.2–0.8% by wt. of Soil	Increased up to 0.4% and then Decreased up to 0.8% dosage

(5% bentonite), S3 (10% bentonite) and S4 (20% bentonite). Higher zeta potential whether negative or positive indicated higher tendency of swelling due to higher repulsion capability of the soil particles. Lower zeta potential resulted in minor tendency of swelling due to unavailability of any force to prevent attraction between the particles. Nano-copper and nano-alumina reduced the zeta potential values of S1 and S2. Nano-copper resulted higher reduction in values than nano-alumina. Nano-alumina slightly increased the zeta value for S3 but reduced by nano-copper. No change in the values with respect to the S4 soil sample was noticed due to higher amount of clay content. Coo et al. (2016) studied highly compressible clay amended with nano-copper and nano-alumina individually. It was observed that W_s increased proportionally with the dosage which indicated less volume reduction. Total volume reduction was decreased by about 10% and 6% with nano-CuO and nano-alumina, respectively, at 2% dosage. The volume reduction was consistent with the increase in dosages. Nano-CuO-treated soil experienced higher reduction in volume than nano-alumina.

Al-Swaidani and Meziab (2021) documented reduction in the free swell index and swelling pressure of nano-amended problematic soils (CL, MH and CH). Nano-natural pozzolana (1% and 2%) and nano-lime (0.6%) was admixed in the soil and modified the microstructure by formation of cementitious gel such as *C–S–H* and *C–A–S–H*. The effective restriction in swelling was observed when soil treated mutually by both the nano-additives. Similarly, Kacha et al. (2022) reported 95% reduction in swelling pressure of expansive soil after incorporation of 40–60% class F fly ash along with 1% nano-lime. A progressive reduction in swelling was observed after curing from 7 to 28 days whereas major decrement was seen in the early curing days. The Formation of Calcium silicate hydrate gel restricted the swelling potential and hence the swell pressure was declined.

2.5.2 Nano-clay

Salemi et al. (2016) modified the swelling characteristics of bentonite in geosynthetic clay liner with nano-clay (10–20%). The amended bentonite managed an increment in free swell index as compared to untreated bentonite. The increase in free swell index was noticed up to 15% nano-content beyond that decrement was recorded. Swell index was enhanced up to 152% at 15% dosage whereas it declined on further addition of nano-clay (20%). Higher swelling was due to increased water absorption capability of nano-treated bentonite due to higher specific surface area of additive which increased the thickness of double diffuse layer. At higher dosage (> 15%) reduction in the swelling tendency may be due to agglomeration of the particles which disturbed the uniform dispersion of nano-clay in the soil matrix. Similarly, Baziar et al. (2018) identified the swelling behaviour of nano-clay-treated kaoline clay and nano-clay-treated sand mixed with 25% clay. The dosage of nano-clay varied from 1–4% for both type of soils. Swelling was enhanced by 31% and 10.64% in the kaoline clay and clayey sand respectively after treatment at 4% dosage of nano-clay. In contrary, Sharo and Alawneh (2016) analysed the swelling potential of expansive clay treated with nano-clay (0.5–3%). Swelling potential of nano-treated soil was consistently reduced with the increase in nano-clay content. Nano-clay particles occupied the intra particle voids in the clay matrix and absorb water due to its higher affinity towards water which caused most of the expansion in the voids. Similarly, Al-Swaidani et al. (2019) examined the impact of Nano-calcined clay (1% and 2%) and Nano-lime (0.6%) on clayey soil. Nano-calcined clay decreased both free swell index and swelling pressure. Nano-lime offered higher swelling than Nano-calcined clay. The effective and maximum reduction in swelling was delivered after simultaneous treatment of soil with Nano-calcined clay and Nano-lime at 2% and 0.6% dosages respectively. The shrinkage was reduced due to pozzolanic reactions between soil and Nano-lime. Linear shrinkage was reduced to half due to reduced plasticity. Qasaimeh et al. (2020) determined the swelling potential of clay added with Nano-clay. The clay was incorporated with Nano-clay in the variation of dosages from 0.2 to 1.2% by wt. of soil. Consistent reduction in swelling was found as the content of Nano-clay increases. The void spaces of the clay matrix were occupied by the Nano-clay which reduced the voids along with their size and provided denser micro structure. A hydrophilic nature of the Nano-clay particles absorbed most of the water and prevented it to interact with soil particles.

2.5.3 Nano-carbons

Taha and Alsharef (2017) documented reduction in both expansive and shrinkage strain of clayey soil treated by Nano-carbons (CNTs and CNFs). The prominent reduction in volumetric strain was recorded up to 0.1% dosage beyond that insignificant reduction was reported. The reduction of 50% in volumetric strain at optimum dosage of 0.10% was noticed due to reduced pore volume and denser microstructure. The soil treated by CNFs observed higher reduction in strain than CNTs due to its higher specific gravity. The agglomeration between particles was noticed on higher dosages above optimum which was responsible for less prominent changes beyond 0.01% dosage. In the same way, Taha et al. (2018) examined the influence of Nano-carbons (CNTs and CNFs) on the volumetric strain of clayey soil samples varied on the basis of different bentonite contents such as 0%, 10% and 20% and named as S1, S2 and S3 respectively. The effective reduction in the shrinkage and expansive strain was reported up to 0.1% dosage of Nano-carbons and then marginal reduction was observed. Dosages above 0.1% bring about agglomeration issues which caused unwanted higher void ratio and resulted to lower density. A decline of 11% in volumetric shrinkage strain was mentioned for S2 and S3 soil samples at optimum dosage. Higher aspect ratio and diminutive dimensions of the Nano-additives resulted in improved volumetric changes. The decrement in volumetric strain of treated soil was also due to increased dry density and reduced moisture content. The treated soil experienced higher interlocking and interfacial force which resulted in advanced frictional and tensile strength. Jia-ming et al. (2022) stated enhancement in swelling of Nano-graphite powder treated expansive clay. This behaviour was attributed to higher specific surface area of the Nano additive which caused higher water absorption in between the clay particles.

2.5.4 Other Nano-additives

Pham and Nguyen (2014) observed reduction in swelling potential of montmorillonite clay treated with iron Nanoparticles with the change in electrolyte background concentration of sodium chloride (NaCl) and potassium chloride (KCl). Swelling magnitude with KCl concentration was found lesser as compared to NaCl as the KCl founds more capable in reducing the electrostatic repulsion in soil particles. Azzam (2014) investigated the influence of Nano-polymer (Polypropylene homopolymer) on clay. The Stabilised soil experienced reduction in axial and diametrical strains. The total volumetric strain was decreased due to Nano-filler due to attainment of hydrophobicity by the soil matrix.

Hanson et al. (2016) observed slight reduction in the swell index value of Nano-silica (0.1–1%) and Nano-silver (1%) treated bentonite soil. Swell index test was founded

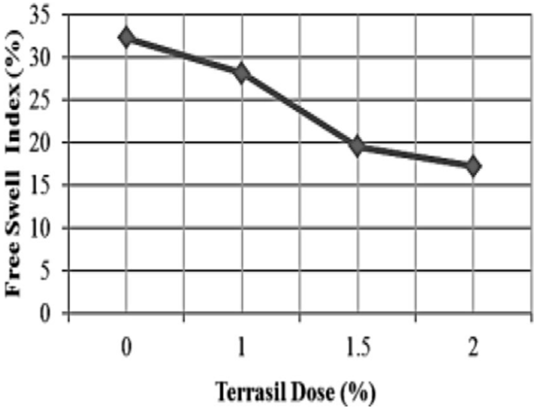


Fig. 12 Change in FSI with Terrasil dosage (Singh, 2017)

insensitive for bentonite soil treated with Nano-silver particles. Swell index value of Nano-silica-treated soil reduced from 25 to 22 and 31 to 28 for dry and wet preparations respectively at 1% dosage. Singh (2017) modified the swelling behaviour of highly compressible clay with Nano-chemical termed as terrasil. Swelling index was prominently reduced up to 1.5% dosage and then marginal decrement was recorded as shown in Fig. 12. The film of adsorbed water in the—treated soil was reduced which was attributed to the reduction in swelling capacity.

Shahsavani et al. (2020) studied the impact of Nano-silica and Electric arc furnace slag (EAF) waste on the swelling and shrinkage potential of Expansive clay. About 77% reduction in swelling potential was recorded after simultaneous treatment of soil at optimum dosage of 0.5% Nano-silica with 20% EAF slag. EAF slag provided higher reduction in swelling potential than Nano-silica when added individually. About 1.6 times lower swelling potential was recorded with EAF slag than Nano-silica. The wetting and drying cycles reduced the axial deformation in both treated and untreated soil where significant change was noticed up to 3 cycles beyond that marginal change was reported. The impact of wetting and drying cycles was also studied on both treated and untreated swelling potential of soil. Nano-silica filled the void spaces and impart denser with more homogeneous soil structure. The cation exchange process between the EAF and clay particles altered the concentration of charges on the clay particle and reduced the thickness of double diffuse layer which ultimately decreased the water absorption. The pozzolanic reactions produced cementitious gels like *C–S–H* and *C–A–H* which bring about more flocculated and agglomerated soil particles which resulted to lower water absorption. The higher dosages of additives above optimum formed unstable large lumps due to non-homogeneous distribution of Nano-material. The density was also reduced on higher dosages due to replacement of more soil particles with finer sized Nanoparticles.

Based upon the existing literature it can be concluded that the swelling and shrinkage tendency of clay is significantly influenced by the type and dose of Nano-additives. Up to a certain amount incorporation of Nano-additives led to reduction in both swelling and shrinkage of soil. Nano-treated soil experienced formation of cementitious gel such as *C–S–H* and *C–A–S–H* which occupied the void spaces and increased the inter particle bonding. Reduced plasticity was also attributed to improved behaviour of swelling and shrinkage in the treated clayey soils. Beyond optimum dose, the increment in the shrinkage and swelling behaviour was noticed which could be credited to agglomeration of particles.

The treated soil observed formation of stronger siloxane bonds (*Si–O–Si*) after conversion of silanol groups (*Si–OH*) during hydration. These siloxane bonds formed hydrophobic layer on the soil particles and restricts the entry of water inside the soil structure. Nano-treatment neutralised the electrical charges of clay and prevent the formation of double water diffuse layer which was responsible for reduction in behaviour of volumetric strain. Most of the Nano-additives other than Nano-clay provided resistivity towards volumetric strain. Nano-clay had possessed very high specific surface area which provide higher water absorption sites during hydrolysis and enhanced the swelling capacity. Whereas on drying greater shrinkage tendency was recorded. Tabular form of the impact of various Nano-additives on highly expansive clays is given in Table 6.

3 Conclusion

From the review of existing literature, the following conclusions can be drawn:

- Nano-stabilisation improves the plasticity characteristics of weak and soft soil by reducing the plasticity index. The mechanism of plasticity modification varies with respect to the Nano-additive and the type of specific soil. Some additives have increased the consistency indices where as some led to decrease depending upon their physical and chemical properties. The inclusion of Nano-silica, Nano-clay, Nano-cement and Nano-carbons (CNfs and CNTs) in soil increases the consistency limits. The rate of increase in W_p was on higher side than W_l which led to reduction in PI. The decrement in W_l and W_p of clay was seen with the inclusion of Nano-copper, Nano-alumina, Nano-MgO, terrasil, Nano-titanium oxide, and Graphene oxide. The inclusion of Nano-material in fine grained soil reduced the W_s.
- Coarse grained soil such as sands, silt, clayey silt, clayey sand etc. experienced increase $\gamma_{dmax.}$ and decrease ω_{opt} after stabilisation with Nano-additives as compared to untreated soil. This was mainly attributed to the very low size of Nanoparticles which were able to fill majority of void spaces both Nano- as well as micro-level in the soil matrix and provided denser soil structure. Also, Nano-additives promoted the advanced pozzolanic reactions which were responsible for generation of cementitious compounds in the form of *C–S–H* and *C–A–S–H*. These hydration products enhanced the aggregation between particles and thus improved the density. The reduction in ω_{opt} was majorly due to restriction of entry of water inside the soil structure due to higher aggregation between the soil particles.
- Majority of fine-grained soils such as silty clays, clays with lower, intermediate and higher compressibility's experienced lower $\gamma_{dmax.}$ and higher ω_{opt} after inclusion of Nano-additives. The reduction in MDD was attributed to the lower specific gravity of Nano-additives than soil particles, whereas the higher OMC was due to availability of higher water absorption sites. The higher specific surface area of the Nano-additives enhanced the water absorption during the hydration process.
- The inclusion of Nanoparticles in the soils had resulted in reduction in consolidation parameters such as compression index, coefficient of compressibility, and volume compressibility. Whereas, the increment in coefficient of consolidation was seen which indicate higher rate of consolidation with lesser settlement. Collapse potential in case of highly collapsible soils such as loess was reduced due to reduction in plasticity and increment in density of the soil structure. Higher reduction in collapse was provided by

Table 6 Effect of Nano-additives on swelling and shrinkage of soil

References	Soil type	Nano-material and other additives	Swelling	Shrinkage
Luo et al. (2012)	Cohesive Clayey Soil	SSA/Cement: (3:1)15% replaced by SoilNano-Al_2O_3: 0%, 1, 2, 3%	Reduced at optimum dose of 1% Nano-content	–
Taha and Taha (2012)	Clayey Soil samples with different bentonite contents	Nano-Alumina: 0.05, 0.075, 0.1, 0.15, 0.3%Nano-Cu: 0.15, 0.3, 0.5, 0.7% Nano-Clay: 0.05, 0.1, 0.15, 0.3, 0.5%	Increased by Nano-Clay, Decreased by Nano-Cu and Nano-Alumina	Increased withNano-Clay Decreased with Nano-Cu and Nano-Alumina
Azzam (2014)	Silty Clay	Polypropylene homopolymer: 0, 5, 10, 15, 20% Curing period: 3, 7, 28 days	Reduced, Swell pressure Reduced up to 86%	Reduced
Pham and Nguyen (2014)	Montmorrolonite Clay	Nano-Silica: 1, 2, 3, 4, 5%Nacl and KCl background concentration: 1.5% and 3% for both	Reduced in both Nacl and KCl but more Reduced by KCl concentration	–
Taha and Taha (2016)	Clay (S1, S2, S3 and S4 with 0%, 5%, 10%, 20% bentonite respectively)	Nano-Copper: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7% Nano-Alumina: 0.05, 0.1, 0.15, 0.2, 0.25, 0.3%	Reduced but S4 sample shows no changes	–
Coo et al. (2016)	Clay	Nano-Cu and Nano-Alumina (Both): 2%, 4%, 6% by dry wt. of Soil	–	Reduced more by Nano-Cu than Nano-Alumina at optimum dosage of 2% each
Hanson et al. (2016)	CH, CL	Nano-Silica and Nano-Silver (Both) Nanoparticle: 0.1% to 1% by wt	Slightly Reduced	–
Salemi et al. (2016)	Bentonite Soil in Geosynthetic Clay liner	Nano-Clay: 0%, 10%, 15%, 20% of bentonite content	Increased up to 15% dosage and then declined	–
Sharo and Alawneh (2016)	Clay	Nano-Clay: 0.1%, 0.4%, 0.6%, 0.7%, 1%, 2%, 3% by wt. of Soil	Reduced, maximum reduction at 3% Nano-dose	–
Taha and Alsharef (2017)	Clayey Soil	Nano-Carbon (CNTs and CNFs): 0.05, 0.10, 0.20% of dry wt. of Soil	Reduced	Reduced

Table 6 (continued)

References	Soil type	Nano-material and other additives	Swelling	Shrinkage
Singh (2017)	CH	Terrasil: 1%, 1.5%, 2%	Reduced up to 1.5% dose and beyond that less prominent reduction took place	–
Taha et al. (2018)	Clay	Bentonite: 0%, 10%, 20% by dry wt. of SoilNano-Carbons (CNTs and CNFs): 0.05%, 0.075%, 0.10%, 0.20%	Reduced (CNFs showed higher reduction than CNTs)	Reduced (CNFs showed more reduction than CNTs)
Baziar et al. (2018)	25% Clay in Sand, Kaoline Clay	Nano-Clay: 1, 2, 3 and 4%	Increased in both Soils	–
Al-Swaidani et al. (2019)	Expansive Clayey Soil	Nano-Calcined Clay: 0%, 1%, 2%Nano-Lime: 0.6%	Reduced, maximum reduction observed at2% Nano-calcined Clay with 0.6% Nano-Lime	Reduced to half as compared to untreated Soil
Shahsavani et al. (2020)	Bentonite Clay	Nano-Silica: 0.1, 0.3, 0.5, 0.7, 0.9% Electric arc furnace slag (EAF): 5, 10, 15, 20%	77% reduction at optimum dose of 0.5% Nano-Silica with 20% EAF	–
Qasaimeh et al. (2020)	Clayey Soil	Nano-Clay: 0.2, 0.4, 0.6, 0.8, 1, 1.2, 1.4%	Reduced	–
Al-Swaidani and Meziab (2021)	Expansive Soil	Nano-natural pozzolona: (1%, 2%) and Nano-Lime (0.6%)	Decreased	–
Jia-ming et al. (2022)	Expansive Soil	Nano-Graphite powder: 0–2.5% by wt. of Soil	Increased	–
Kacha et al. (2022)	Expansive Soil (CH)	Nano-Lime:0–1%, Fly ash:20–60% by wt. of Soil	Decreased	–

Nano-clay as compared to other Nano-additives due to its higher specific surface area than other particles.

- Permeability of the weak soil also reduce with the inclusion of Nano-additives which is beneficial for its applications in landfill barriers, canal lining, lining of core in earthen dams etc.
- Nano-materials such as Nano-silica, Nano-CuO, Nano-alumina, Nano-carbons, Nano-lime and Nano-cement have reduced the swelling and shrinkage behaviour of fine grained weak and soft soils. Nano-clay has contradictory results as some studies reveal reduction in swelling potential whereas some studies reflected inverse impact.
- Nano-CuO resulted to higher resistivity towards swelling and shrinkage as compared to Nano-alumina due to its higher specific gravity. Soil treated with CNFs experienced lesser volumetric strains as compared to CNTs due to its delusional dimensional aspects.
- On economical basis, the cheapest Nano-additive is found to be the Nano-clay or other Nano-soil particles as they are transformed from the base soil particles only. The majority of the Nano-additives have similar costing except Nano-carbon, Nano-copper and Nano-titanium oxide. Nano-copper and Nano-titanium oxide might reflect toxicity at the time of infusion and they should be handled carefully. Other Nano-additives deliver non-toxicity, higher price/performance ratio and are environment friendly which makes them recommendable for the soil stabilisation of weak and soft soil.
- The majority of the Nano-additives fall under the criteria of sustainability except some metal-based additives such as Nano-titanium oxide, Nano-copper as they are not cost effective and could reflect the problems of lung inflammation during the period of infusion. Nano-additives such as colloidal silica, Nano-silica, Nano-alumina, Nano-magnesium oxide, Nano-clay are based on silicon dioxide, aluminium oxide, magnesium oxide which also found in the composition of soil. These materials are inert and have non-toxic nature. The application of Nano-additives reduces the consumption of pozzolanic materials (cement) in the soil stabilisation during mutual treatment due to increased reactivity which directly influences the cost and the carbon footprints.

4 Future scope

From this detailed review of literature, it can be concluded that it is advantageous to incorporate Nano-additives to improve the geotechnical properties of weak soil. The improvement in the geotechnical properties of soil is governed by the content and type of Nano-additive used. Nano-additives alone definitely impart significant improvement in the geotechnical properties but the addition of pozzolanic materials such as cement and lime mutually provided higher modification in the engineering properties of soil. The Nano-additives improved the uniform dispersion of pozzolanic materials in the soil structure which upgrade the reactivity at Nano- and micro-scale. The application of Nano-additives reduces the consumption of pozzolanic materials due to increased reactivity and directly influences the cost. Majorities of the investigation carried out in the past are focused on the evaluation of change in Atterberg's limits, compaction, consolidation, permeability, swelling and shrinkage of weak soil with the inclusion of different type of Nano-additives. Limited studies are available on the effect of incorporation of Nanoparticles on the tensile strength, durability performance such as freeze and thaw cycles, wetting and drying cycles, and leachability of soils. The influence of Nano-silica on consolidation as well as swelling and shrinkage behaviour of problematic soils needs proper study. The impact of Nano-clay on swelling potential is still a question due to projection of contrary results which raised a need for further deep experimental analysis. The effect of Nano-additives on the Dynamic properties of loose sands prone to liquefaction has not been addressed. Very few authors have used Graphene oxide, Nano-structured biomass ash, Nano-structured waste paper ash, Terrasil, Nano-polymer etc. in stabilisation of problematic soils.

Authors contributions Conceptualisation and Methodology: Dr. JSY Formal analysis and investigation and Writing—original draft preparation: Mr. VC Writing—review and editing: Dr. JSY and Prof. RKD Supervision: Dr. JSY and Prof. RKD.

Data availability Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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