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STATE OF THE ART/PRACTICE PAPER

The Impact of Nano-Silica and Nano-Silica-Based Compounds on Strength, Mineralogy and Morphology of Soil: A Review

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Abstract Because soft clays have a greater tendency to swell and shrink, structures constructed on them face the danger of suffering uneven settlement, which may result in structural damage. Numerous attempts have been made to stabilise the soil by the mean of mechanical and chemical stabilization. In recent years, several researchers intended to change the geotechnical characteristics of problematic soils with the help of Nano-additives such as Nano-silica, Nano-clay, Nano-lime, Nano-carbons. This study is focused on summarising the change in strength, mineralogical and morphological behaviour of soil with the incorporation of Nano-silica and Nano-silica-based compounds reported by researchers. It was observed that strength of soil improved drastically with the addition of Nano-silica and Nano-silica-based compounds up to optimum dosages. The inclusion of Nano-silica densifies soil due to the filling effect, formation of better interparticle bond and pozzolanic products. From the detailed review of literature, it can be concluded that it is advantageous to incorporate Nano-silica and Nano-silica-based compounds to improve the geotechnical properties of problematic soils.

Keywords Weak soil · Nano-silica and nano-silica-based compounds · Strength · Microstructure

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Introduction

The term Nano-technology was first mentioned by 'R Feynman' in his lecture "there's lots of space at the bottom" in 1960. In 2007, National Nano-technology initiative defines the term Nano-technology as the manipulation of matter with at least one dimension sized from 1 to 100 nm. One Nanometre is equivalent to 10^{-9} of a meter, same as the size if a comparison is made between a marble and size of earth. Nanotechnology has been widely used in different sectors such as medicines, agriculture, sports, electronics. From the past few years, the researchers are carrying out investigation on the beneficial utilization of Nano technology in the civil engineering works such as construction of pavement and embankment, liner material for canals, concrete.

Weak or soft soils are not suitable to bear structural loads and could damage the property in long term which may lead to economical as well life losses. Weak clayey soils are prone to larger uneven settlement due to low shear strength. So, engineers have to alter the geotechnical properties of existing soil by the mean of ground improvement (compaction, grouting, blasting etc.), or ground reinforcement (stone column, fibres, geosynthetics etc.) [1–4] or ground treatment (cement, lime, fly ash etc.) [5]. The weak soil has been widely stabilized in the past with the help of traditional materials such as cement, lime, sodium silicate, acrylate. From the past few years, usage of Nano-additives to improve the geotechnical properties of soil is gaining popularity. The inclusion of Nano-additives changes physical and chemical properties of soil. Further, the usage of Nano additives can lead to reduction in the amount of dosage of cementations material (cement, lime etc.) required to alter the geotechnical properties of soil [6]. Nano-materials such as Nano-silica, Nano-clay, Nano-copper oxide, Nano-alumina, Carbon Nano-fibres such as CNTs and CNFs, laponite, Nano-MgO, Graphene oxide Nano-sheets have been used by different researcher to treat different types of soils. The applicability of type of Nano-particle depends on the type of soil and geotechnical property which is to be modified such as strength, settlement, permeability, volumetric strain as per the field required. The collapse potential of poorly graded sand was reduced significantly after addition of nano-silica fume [7]. Haeri and Valishzadeh [8], Kamgar et al. [9], Jiang et al. [10] incorporated nano-clay in low compressible silt, clayey sand and lime treated clay, respectively, and recorded significant improvement in the compressive strength. This was mainly attributed to the formation of extra cementitious compounds such as C–S–H and C–A–S–H in the soil matrix due to promotion of pozzolanic reactions between soil and nano-clay particles. The shear strength parameters such as cohesion and internal friction angle were enhanced after incorporating nano-clay in silty soil and clay as reported by Bahari et al. [11] and Changizi and Haddad [12], respectively. Such behaviour was attributed to the improved bonding properties between soil particles by nano clay. Majeed and Taha [13] and Mir and Reddy [14] experienced enhancement of compressive strength in clay and highly compressible clay, respectively, after addition of nano-copper. The advance formation of interlocking between soil particles was obtained after pozzolanic reactions offered by nano-copper led to such improved compressive strength. Corriea et al. [15] reported hike of 47.9% in compressive strength of cemented sandy clay after treatment with multi-walled carbon nano-tubes. Taha and Alsharef [16] observed reduction in swelling and shrinkage property of clay with help of carbon nano-fibres and carbon nano-tubes. Nano-carbons act as bridges between soil grains to transfer load after shrinkage and expansion and resisted the crack intensities. The California bearing ratio of sewage sludge ash treated cemented clay was significantly enhanced after incorporation of nano alumina particles. The undrained shear strength of the low compressible silt was improved by nano alumina as reported by Mir and Reddy [17]. Such changes were due to formation of new pozzolanic compounds after cation exchange reactions. The prominent improvement was observed in silty soil after admixing graphene oxide nano-sheets [18]

The influence of sea water on the durability of soil mass treated with nano calcium carbonate was addressed by Meng et al. [19]. The seawater around the soil mass consisted of sulphuric acid which has the potential to reduce durability and its compressive strength by offering higher erosion conditions. The impact of corrosion due to marine environment was found to be reduced after incorporating nano-calcium carbonate. Similarly, Yao et al. [20] analysed the impact of sulphuric acid attack on the compressive strength of cemented silty clay treated with nano magnesium oxide. Acid attack led to the reduction in strength and displayed gentler stress strain curves which denoted the lower stiffness of the soil matrix. The involvement of nano-magnesium oxide reduces the influences of acid attack which was attributed to the improved soil structure by filling of void spaces by the cementitious compounds formed after hydration reactions. Aksu and Eskisar [21] found reduction in the loss in strength caused due to thermal cycles in cemented clay after treatment with nano-silica. This was credited to the advanced bonding characteristics developed with the help of pozzolanic materials formed by nano-silica.

This study aims to provide a critical overview of prior research conducted by a several researchers and pave the way for potential future research in this field. The study is strictly limited to the summarised the impact of inclusion of Nano-silica and Nano-silica-based compounds on the shear strength, California Bearing Ratio (CBR), mineralogy and morphology of soil reported by researchers. The impact of Nano-additives on other properties such as Atterberg's limit, compaction, consolidation, permeability, swelling and shrinkage of soil have already been documented [6].

Physical and Chemical Properties of Nano Silica

Silica is present in the form of quartz which almost covers the 10% of the crust mass on earth. The chemical form of silica with particles sizes in Nano-scale known as Nano- and colloidal silica. The size of both Nano- and colloidal silica particles varies from 1 to 100 nm. Nano-silica is an amorphous powder which is bright white in colour as shown in Fig. 1a. Whilst colloidal silica is a suspension of Nano-sized silica particles in the liquid medium as shown in Fig. 1b. These particles are amorphous and non-porous in nature. Colloidal silica is hydrophilic in nature due to formation of hydrogen bonds. The surface of the particles is covered by siloxane and silanol groups after coming in contact with water which forms hydrogen bonds and makes it hydrophilic in nature. The size of both Nano- and colloidal silica particles varies from 1 to 100 nm. The physical and chemical Properties of Nano-silica is reported in Table 1.

Shear Strength Behaviour

This section of paper discusses the effect of Nano-silica and Nano-silica-based compounds on the shear strength of soil, cemented Soil, and fibre reinforced soil examined through unconfined compressive strength test, direct shear test and triaxial shear strength test.

Unconfined Compressive Strength

Soil Treated with Nano-Silica and Nano-Silica-Based Compounds

Moharram et al. [22] documented maximum increase in the UCS of low compressible clay at optimum dosage of 1.5%

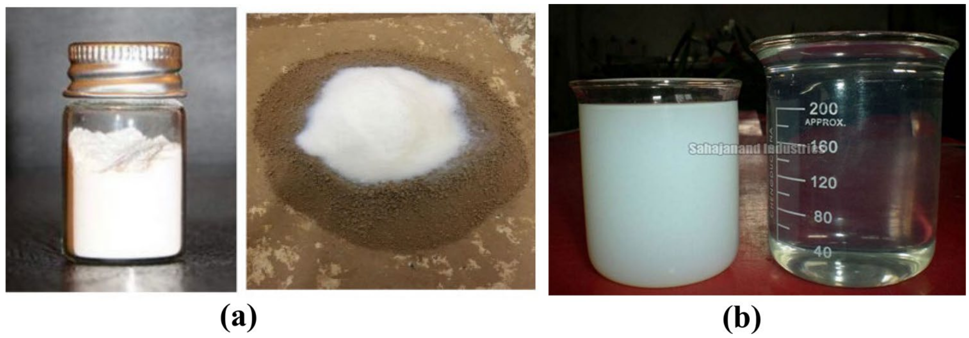


Fig. 1 **a** Nano-silica powder [50]. **b** Colloidal silica [50]

Table 1 Physical and chemical properties of various Nano-silica [51, 63]

Physical property		Chemical composition	
Bulk density (g/cc)	0.1	SiO_2 (%)	99.7
Specific surface area (m^2/gm)	600–785	Ti (%)	0.012
Average particle size (dia) nm	11–13	Na_2O (%)	0.007
Form and colour	White powder	CaO	0.005
Solubility in water	Insoluble	Fe_2O_3	0.002
Melting point (°C)	1726	Others	0.274
Application as soil stabiliser	Reinforcement and reduced soil settlement		

Nano-silica and 1% Nano-kaolinite. The higher Nano-content above optimum led to reduction in strength because of agglomeration. Whereas Changizi and Haddad [23] stated advancement in peak shear strength of the cohesive soil up to 0.7% Nano-silica dosage. Beyond that reduction in rate of gain in strength was noticed. The residual strength and peak failure strain showed continuous decrement on increasing Nano-silica content. Nano-silica absorbs the water present inside the soil to produce viscous gel at constant moisture content and reduced the compressibility of soil. Similar observation was also noticed by Moayed and Rahmani [24] and García et al. [25], but the maximum improvement in the strength was witnessed at 4 and 3% dose, respectively. The strength modification was attributed to the chemical reactions between nano-silica and clay particles which improved the bonding. Shaker [26] stated that the curing period plays the vital role in gain of strength. About 6.65 times improvement in the compressive strength was witnessed by Hu et al. [27] at 5% Nano-silica content as compared to untreated soil. Nano-silica transforms the plastic behaviour of soil to the brittle [28]. The formation of viscous gel took place which filled up the void spaces and provided denser soil structure along with blockage of water passage inside the matrix. The gel improved the interlocking and bonding between the soil particle which may led to the strength improvement. Contradict to this Malik et al. [29] reported continuous gain in strength with the increase in Nano-silica from 5 to 20% by weight of soil. This improvement was due to formation of silicate pozzolanic compounds during hydrolysis between nano silica and clay particles. Ahmadi and Shafiee [30] enhanced the compressive strength of clayey soil with Nano- and Micro-silica (0.2–6%). The reduction in rate of gain in strength was reported with higher dosages (above 2%) because of clustering between the Nano-particles. Similarly, Kalhor et al. [31] reported maximum increment in compressive strength of clayey soil up to 2% inclusion of Nano-silica. Freeze thaw cycles reduced the compressive strength as the number of cycles increases but crossing 6 cycles showed less reduction. The reduction in strength showed by Nano-treated soil was lower as compared to untreated soil subjected to same freeze thaw cycles. The thermal cycles increased the intensity of crack propagation which reduced the cohesion and interlocking between the particles. Whereas Changizi et al. [32] reported increment of 50% and 47% was obtained in peak strength of clayey soil treated with 1% (optimum dosage) Nano-silica as compared to natural soil after 9 and 12 thermal cycles at optimum dosage of 1% Nano-content, respectively. This was attributed to higher resistant offered by Nano-silica against strength reduction against thermal cycles. Parsakhoo [33] employed Nano-silica along with horsetail ash to stabilise clayey soil samples (CH and CL). The optimum limit of additives to attain maximum strength for Nano-silica and horsetail ash was 1.5 and 3%, respectively. Nano silica has high specific surface area which permitted higher reactivity with the soil particles and showed high pozzolanic activity. The silica present in the Nano-silica reacts with the calcium and hydroxide ions present in the soil and forms cementitious gel (C–S–H) which filled the gap between the soil grains and improvise the bonding characteristics. Haeri and Valishzadeh [8] observed that Nano-silica (0.1% dosage), Nano-clay (0.4% dosage) and Nano-calcium carbonate (0.2% dosage) enhanced the strength of collapsible soil classified as ML up to 2.26 times, 2.7 times and 2.78 times than untreated soil, respectively. Nano-silica imparted greater stiffness than other two additives. The improved bonding between soil particles with newly formed cementitious compounds after completion of sufficient duration of curing period resulted to the higher compressive strength. Chaudhary et al. [34] reported maximum improvement in the unconfined compressive strength of bentonite with inclusion of 0.8% Nano-silica content. The nano-silica enhanced the pozzolanic reactions due to their higher reactivity with the hydrolysis of bentonite particles. Nozari et al. [35] observed maximum improvement in the strength of silty sand with inclusion of 15% Colloidal silica along with 10% content of fines in sand. The impact of various environmental conditions (pure water, acid water, sea water and dry air) on the compressive strength of nano-silica treated sand was studied by Cheng et al. [36]. All the environmental conditions were found responsible for reducing the compressive strength of the treated soil with increase in the soaking period. The maximum reduction was found in dry air, and minimum reduction was observed with pure water condition. In dry air environment, strength was reduced significantly after 365 days due to higher shrinkage provided by nano-silica whereas 40–50% strength reduction was observed in acidic and sea water condition on comparison with the maximum strength obtained in pure water condition after 365 days. The nano-silica particles reduced the impact of various environmental conditions due to wrapping and bonding of particles. The newly formed pozzolanic compounds act as fastening agent between soil particles. In dry air, initially nano-silica offer adsorption and nano-filling effect to fill the pore spaces between the sand particles. After certain duration of soaking period, the effect of adsorption and filling was gradually decreased due to shrinkage and roughening. The destruction of nano-silica particles between the soil particles was observed after soaking in dry air which led to cracks and holes. Pure water-soaked samples reveals several cracks inside the structure, whereas corrosion was reflected in sea and acidic soaked samples. A chapped and shredded phenomenon were seen in dry air-soaked samples due to lack of moisture content.

Cemented Soil Treated with Nano-silica and Nano-silica-Based Compounds

Bahmani et al. [37] reported maximum improvement in the strength of clayey soil treated with 0.4% Nano-silica and 8% cement. They observed that 15 nm Nano-sized particles provided better results than 80 nm size due to their higher specific surface area which led to higher packing density with effective dispersion inside the soil structure, Whereas higher dosages of Nano-silica led to decrement in the compressive strength due to poor dispersion inside the soil matrix, nano-particles accelerated the cement hydration with higher amount of C–S–H gel formation. This viscous gel binds the soil particles and increased the internal resistance. This gel was formed after ion exchange mechanism process between nano-silica and calcium hydroxide. The addition of cement increases the amount of calcium hydroxide which was further utilised by nano-silica added and natural present silica in the soil to form extra cementitious gel which was responsible for further enhancement in the strength. Ghasabkolaei et al. [38] mentioned 1.5% of Nano-silica as optimum dose for maximum increase in compressive strength of cement treated loess soil. The dosage of nano-silica above 1.5% reduced the compressive strength due to agglomeration of Nano-particles. The agglomeration phenomenon formed weak lumps and reduced the C–S–H gel formation. Nano-additives reflects unique engineering properties due to their higher specific surface area than traditional additives [39]. This behaviour of nano additives provides higher level of reactivity with the soil particles at both nano as well as micro-scale in a more uniform and homogeneous way as compared to traditional stabilisers such as cement and lime. The nano-additive's delivers better ion exchange capacity due to higher interaction with the soil particles as compared to traditional additives [23]. Haeri et al. [40] examined the UCS behaviour of loess soil incorporated with Nano-silica (2–7%), lime (1–5%) and cement (1–1.5%) individually and mutually. Nano-silica treated soil showed maximum gain in strength at early stage of curing. Whereas Lime and cement treated soil required curing to attained maximum strength. Both Nano-silica and lime treated soil attained maximum strength up to 3% dose (optimum) beyond that less prominent change appeared. UCS improved by 4 times with Nano-silica at optimum dose in 3 days. Nezhad et al. [41] reported improvement in the strength of gas oil contaminated clay soil up to 2% Nano silica dosage. The Viscous gel was produced by Nano-silica which binds the particles more prominently then adsorbed water. Where higher dosage led to agglomeration of particles which resulted to reduce strength, Kulanthaivel et al. [42] compared the influence of Nano-silica and white cement on strength of clay. Both the additives improved strength up to 7% dosage. The maximum enhancement of 7.01 times was received with the inclusion of 2% Nano-silica with 3% white cement in soil. Ghavami et al. [43] incorporated the cement kiln dust (15%) treated clay with Nano-silica (0.5–2%) and silica fume (5–15%). The silica fume and Nano-silica improved the strength after 14 and 28 days of curing. Strength was improved by 19.5 and 17.5% at 15% silica fume dosage after 14 and 28 days, respectively, as compared to cement kiln dust treated soil. Nano-silica increased the strength up to 1% dosage beyond that decrement was observed. The strength modified by Nano-silica was more significant than silica fume due to its higher specific surface area which resulted to higher reactivity. Both the additives formed additional viscous Calcium silicate hydrate gel after reacting with calcium hydroxide during the hydration process. The dispersion problem was raised at higher dosages (2%) of Nano-silica due to agglomeration of particles which cause strength reduction. Choobbasti et al. [44] reported improvement in the strength of cemented sand with inclusion of Nano-silica up to 10%. The consumption of calcium hydroxide during the ion exchange process led to the formation of calcium silicate hydrate gel. This gel formation increased the inter particle bonds and imparted strength enhancement with more homogeneous and durable microstructure. Beyond 10% dose, a declination in strength was reported as revealed in Fig. 2. In another study, Choobbasti and Kutanaei [45] evaluated the influence of Nano-silica (4–12% by wt. cement) on unconfined compressive strength of cemented sandy soil and informed prominent growth in strength with the increase in Nano-content. The enhancement in strength was noticed up to the dosage of 8% Nano-silica content. The viscous gel formed after chemical reactions improved the cohesive strength between sand particles and thus, resisted the movement of grains. Ahmadi [28] also reported the same behaviour of fine sand treated with Nano-silica. Bargi et al. [46] studied the influence of micro (silica fume) and Nano-silica particles (Nano 200 and Nano 380) on the cemented clayey sand with the variation of fines in soil such as silt, kaolinite and bentonite in the soil. On comparing the type of silica products, increment ratio after 7 days was 14, 19 and 22% for silty fine soil treated with silica fume, Nano 200 and Nano 380, respectively, at fixed dosage 0.5% by wt. of cement. This ratio of increment reduced after 28 days of curing. The maximum compressive strength was received with 0.5% content of Nano-silica 200 in silty fine soil because of higher dry density of mixture at this dosage. Aksu and Eskisar [21] demonstrated the influence of

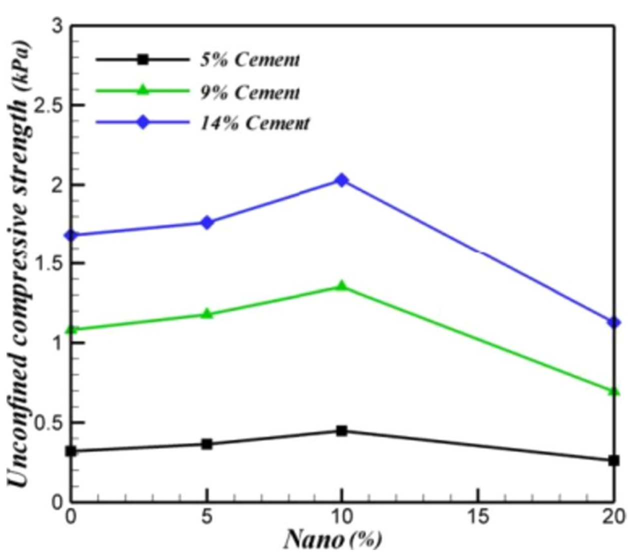


Fig. 2 Variation of UCS with Nano-silica and cement [30]

Nano silica (0.3, 0.5 and 0.7%) and cement (5 and 10%) on clay, sand and clayey sand. Nano-stabilised soil experienced higher resistivity towards strength and weight loss than natural soil subjected to thermal cycles (freeze and thaw). The observed strength of 10% cement treated clay was nearer to 5% cemented clay treated with 0.5% Nano silica. The reduction in cement consumption was recorded in the study. The major advantage of adding nano-material along with the cement is that it significantly reduced the usage of cement and provides better results than higher dosages of cement stabilisation. The nano-material due their higher specific surface area improved the dispersion of cement in a more uniform and homogeneous way inside the soil structure. This increased the reactivity of cement with the soil particles and generates extra amount of cementitious gel in the form of *C–S–H* and *C–A–S–H* during ion exchange process. The formation of extra amount of pozzolanic compounds in the form of viscous gel further improves the strength and deformation properties of soil. In 5% cemented soil, the optimum dosage of Nano-silica for clay, clayey sand and sand was 0.5, 0.3 and 0.7%, respectively. These dosages provided maximum resistance towards strength loss due to thermal cycles as compared to natural or soil treated with other dosages. The minimum loss in strength and weight in case of clayey sand was observed with 10% cement with 0.5% Nano silica. Only 8% loss in strength was mentioned. The higher dosage of Nano-silica led to agglomeration effect in clay and clayey sand. Luo et al. [47] demonstrated the influence of Nano-silica (1.5–6% by wt. of soil) on cement stabilised calcareous sand at 7 and 14 days of curing. Cement was taken as 10% by wt. of soil. Nano-silica improved the strength by 2.29 and 2.08 times as compared to cement stabilised sand after 7 and 14 days at optimum dosage of 4.5% Nano-silica. Chen et al. [48] examined the influence of nano-silica (1, 2 and 3%) on cemented soil in sea water condition. The 2% nano-silica dosage delivered maximum gain the compressive strength. About, 86 and 158% improvement in strength were exhibited by the nano-silica treated cemented after 30 and 60 days of curing. Superior filling and pozzolanic properties of nano-silica imparts such changes in strength.

Fibre Reinforced-Cemented Soil Treated with Nano-silica and Nano-silica-Based Compounds

Changizi and Haddad [49] observed improvement in UCS of clay with addition of Nano-silica and recycled fibres. The combination of 1% Nano-silica with 0.3% fibre content was considered as optimum dosage with significant improvement in both peak and residual UCS, whereas above that less prominent gain was noticed as shown in Fig. 3. Nano-silica improved the stiffness whereas fibre imparted the strain hardening. Tomar et al. [50] incorporated Nano-silica (1–7%) and polypropylene fibres (0.1–1.3%) in clay and experienced higher strength than untreated soil. The optimum dosage was represented as 7% Nano-silica with 0.7% PPF at which maximum strength was received as shown in Fig. 4. The impact of thermal cycles on clay treated by nano-silica and glass fibre was documented by Ahmadi et al. [51] and found reduction in the compressive strength after freeze and thaw cycles. The reduction in the strength was reduced after treatment with nano-silica and glass fibre and reported that clay mixed with 1.5% nano-silica with 1.5% glass fibre content shows best resistance to the strength reduction caused by the thermal cycles. The effect of Nano-silica and Nano-silica-based compounds on unconfined compressive strength of soil with key findings and optimum dosage is summarised in Table 2. Fig. 5 represents the strength improvement factor of clayey soil with optimum dose observed by various researchers.

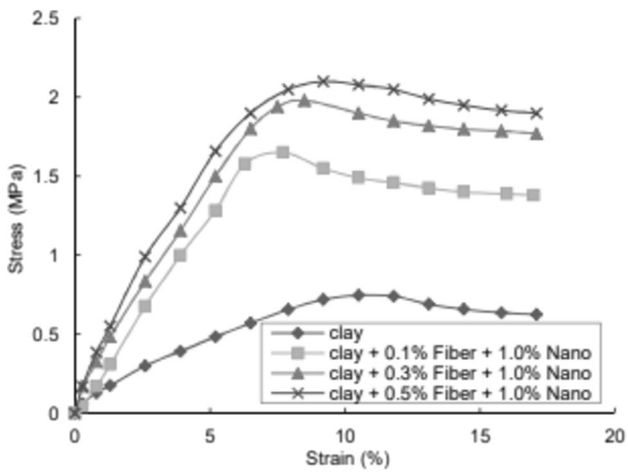


Fig. 3 Stress strain behaviour of clay amended with fibre and Nano-silica [49]

Direct Shear Strength

Soil Treated with Nano-Silica and Nano-Silica-Based Compounds

Moharram et al. [22] analysed the shear characteristics of low compressible clay soil treated with Nano-silica (0.5–2.5%) and Nano-kaolinite particles (0.5–2%). Maximum improvement in the cohesion of clayey soil was achieved at 1% Nano-Kaolin and 1.5% Nano-silica. No significant changes in friction angle were observed. Similarly, at 1% Nano-silica content, the maximum improvement in shear strength of cohesive soil was reported by Changizi and Haddad [23]. An enhancement of 1.23 and 2.1 times was stated in cohesion and friction angle at 1% dosage of Nano-silica, respectively. The inclusion of Nano-silica reduced the interspacing between the clay particles by formation of viscous gel which increased the interfacial contact area and improved the frictional and cohesion properties. In another study, Changizi et al. [32] reported reduction in the shear strength of clay stabilized with Nano-silica subjected to freeze and thaw cycles, but the impact of strength reduction

Fig. 4 Strength of clayey soil incorporated with Nano-silica (1–7%) and polypropylene fibres [50]

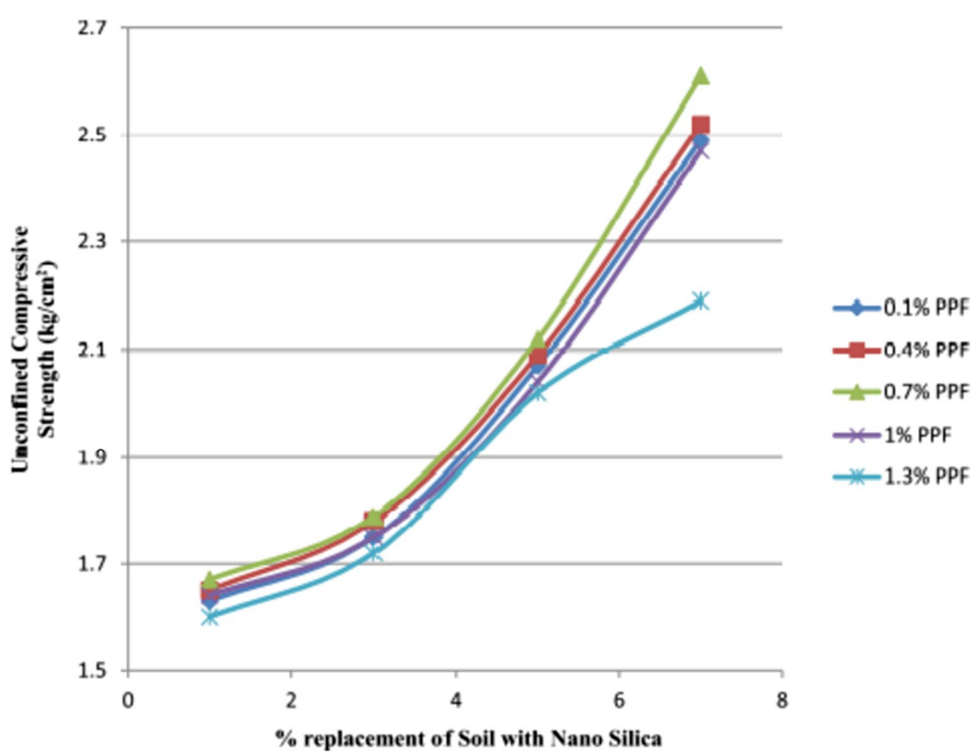


Table 2 Effect of Nano-silica and Nano-silica-based compounds on unconfined compressive strength of soil

References	Soil type	Dosage of nano additive (%)	Dosage of primary additive (%)	Observation (s)	Optimum dosage of nano-additive (%)	Optimum dosage of primary additive (%)
[37]	Clay	Nano Silica: 0, 0.2, 0.4, 0.8, 1% by wt. of soil	Cement: 4, 6, 8% by wt. of soil	Increased	0.4%	Increased up to 8%
[44]	Sand	Nano Silica: 0, 5, 10, 15% by wt. of sand	Cement: 5, 9, 14% by wt. of sand	Increased up to 10% Nano-silica dosage and then reduced	10%	Increased up to 14%
[49]	Soft clay	Nano Silica: 0.5, 0.7, 1% by wt. of soil	Recycles polyester Fibre: 0.1, 0.3, 0.5% by wt. of soil	Increased	1%	0.3%
[40]	Loess soil	Nano Silica: 2, 3, 5, 7% by wt. of soil	Cement: 1, 2, 4.5% by wt. of soil lime: 1, 3, 5% by wt. of soil	Enhanced up to optimum dosage of 3% Nano Silica	3%	Cement: 4.5% Lime: 3%
[22]	Low compressible clay	Nano Silica: 0, 0.5, 1, 1.5, 2, 2.5, 3% by dry wt. of soil	–	Increased up to 1.5% Nano Silica dosage and then declines	1.5	–
[23]	Cohesive clay	Nano Silica: 0.5, 0.7, 1% by wt. of parent soil	–	Peak strength increased up to 0.7% and then reduced whilst residual strength showed consistent reduction	0.7%	–
[38]	Clay	Nano silica: 1, 1.5, 2, 3%	Cement: 9%	Maximum enhanced at 1.5% Nano-silica dosage beyond that decreased	1.5%	–
[45]	Sandy soil	Nano-silica: 0, 4, 8, 12% by wt. of cement Curing period: 7, 28, 90 days	Cement: 6% by dry wt. of soil	Increased up to 8% Nano-silica and then decreased	8%	6%
[12]	Clay	Nano-silica: 0.5, 0.7, 1%	–	Increased peak strength up to 0.7% Nano content and then reduced whilst residual strength continuously declined	0.7%	–
[24]	Kaolinite clay	Nano-silica: 1, 2, 3, 4, 5% Curing period: 1 day	–	Increased up to 4% dosage and then reduced	4%	–
[25]	Lacustrine soft clay	Nano-silica: 0.5, 0.7, 1, 3% by dry wt. of soil	–	Increased	3%	–
[26]	Clayey soil	Nano-silica: 0, 0.5, 1, 1.5, 2, 3% Curing period: 7, 14, 28 days	–	Increased up to 3%	3%	–
[27]	Silty clay	Nano-silica: 0, 0.25, 0.5, 0.75, 1, 2, 3, 5% by wt. of silty clay	–	Increases up to 5%	5%	–
[29]	Clay	Nano Silica: 5–20% by wt. of dry soil	–	Increases up to 20%	20%	–
[30]	Clay	Nano-silica and micro-Silica: 0–6%, 28 days curing time	–	Increased	2%	–
[31]	Clayey soil	Nano-silica: 0, 1, 2, 3, 4% Curing period: 42 days	–	Increased up to 2% Nano dosage and then reduced	2%	–

Table 2 (continued)

References	Soil type	Dosage of nano additive (%)	Dosage of primary additive (%)	Observation (s)	Optimum dosage of nano-additive (%)	Optimum dosage of primary additive (%)
[33]	CL and CH	Nano-silica: 0.5, 1, 1.5, 2% Curing period: 7, 14, 28 days	Horsetail ash: 1, 2, 3 and 4%	Increased	CH: 1.5% CL: 1%	CH: 3% CL: 2%
[50]	Clay	Nano-silica: 1, 3, 5 and 7% by weight of soil	Polypropylene fibre: 0.1, 0.4, 0.7, 1 and 1.3%	Increased	7%	0.7%
[41]	Gas oil contaminated clayey soil	Nano-silica: 1, 2 and 3%	Gas oil contamination: 3, 6 and 9% Hydrated lime: 1, 2 and 3%	Gas oil increased the strength up to 3% dose and then reduced, Nano Silica alone showed maximum gain at 2%, Hydrated lime showed max. strength at 3% dose; whilst mixture showed greatest gain in strength at 3% dose of both in 1:1	2%	Gas oil: 3% Hydrated lime: 3%
[42]	Clayey soil	Nano-silica: 3, 5, 7, 9%	White cement: 1, 2, 3, 4%	Both the additives showed increment alone, but greatest increment was observed when mutually treated the soil at 2% Nano Silica with 3% white cement	2%	3%
[8]	Loess collapsible soil	Nano-silica: 0.2, 0.4, 0.6, 0.8 and 1%		Increased	0.1%	–
[35]	Silty sand	Colloidal Silica: 5, 10, 15%	Silt: 10, 20 and 30%	Increased and maximum at 15% colloidal Silica with 10% silt	15%	10%
[43]	Clay	Nano-silica: 0.5, 1 and 2%	Silica fume: 5, 10 and 15%, Cement kiln dust: 15%	Increased by both and maximum value achieved at 1% Nano Silica dose	1%	–
[46]	SC	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	Accelerated gaining of strength at early ages, 0.5% Nano dose provide greater strength	0.5%	–
[51]	Clay against thermal cycles	Nano-silica: 0.5, 1, 1.5%	Glass fibre:1.5, 2.5, 3.5%	Strength reduced after thermal cycles, maximum resistant to strength reduction was provided by 1.5% Nano Silica with 1.5% glass fibre	1.5%	1.5%
[32]	Clay	Nano-silica: 0.5, 1, 1.5%	–	Increased UCS by 50% at optimum dose of 1%, also reduces the effect of thermal cycles	1%	–

Table 2 (continued)

References	Soil type	Dosage of nano additive (%)	Dosage of primary additive (%)	Observation (s)	Optimum dosage of nano-additive (%)	Optimum dosage of primary additive (%)
[21]	Clay, Sand and Clayey sand	Nano-silica: 0.3, 0.5 and 0.7%	Cement: 5 and 10%	Nano-additive reduces the cement consumption, Strength observed in 10% cement treated clay was nearer to 5% cemented clay treated with 0.5% Nano-Silica	0.5%	–
[48]	Silty clay	Nano-Silica: 1, 2 and 3%	Cement: 15%	Increased	2%	–
[34]	Bentonite	Nano-Silica: 0.2, 0.4, 0.6, 0.8 and 1%	–	Increased up to 0.8%	0.8%	–

on nano-silica stabilised soil was lesser than the natural clay. Aksu and Eskisar [21] studied the impact of Nano-silica (0.5%) on shear strength of clay, clayey sand and sand. The cohesion in clayey sand and sand was prominently improved, whereas the angle of internal friction was slightly reduced. The treated clay showed higher improvement in angle of internal friction than cohesion. The viscous gel formed during the chemical reaction surrounded the grain surfaces and provided higher adhesion between the particles which might be the reason for enhanced cohesion. Hussien et al. [52] reported increment in frictional angle and cohesion of Nano-silica treated sand. This was attributed to the filling of void spaces inside the sand structure by nano-silica.

Kakavand and Dabiri [53] stabilised the sandy silt mixture by injecting Colloidal Nano-silica solution (5%) and observed that both cohesion and angle of internal friction in Nano-injected was more compared to non-injected state of soil (dry and saturated both). Al-Obaidi et al. [54] compared the impact of silica fume (5, 10 and 20%) and Nano-silica fume (1, 3 and 5%) on the shear parameters of poorly graded sand. The improvement in cohesion with the addition of silica fume (with 10% dosage) and Nano-silica fume (with 3% dosage) was up to 350% in dry state and 43–47% in soaked state. It was stated that the lower dosage of Nano-silica fume (3%) was sufficient to reach the same increment in cohesion as that of 10% silica fume. This behaviour was credited to the higher specific surface area of the Nano-silica fume. At the optimum dose of 3%, angle of internal friction was improved by 10–20% and 3–7% in dry and soaked condition, respectively. The reduction in angle of internal friction was observed with the addition of silica fume. The major reduction in friction angle was observed up to 5% silica fume dose beyond which slight increment was observed but was still lesser than the untreated sand. Silica fume has a very adhesive nature and demands higher water for the completion of hydration process. The silica fume particles are less coarse than gypsum sand particles which provides lesser frictional resistance.

Fibre Reinforced Soil Treated with Nano-silica and Nano-silica-Based Compounds

Changizi and Haddad [49] investigated the impact of Nano-silica and recycled polyester fibre on shear strength parameters of soft clay. The maximum improvement in cohesion and angle of internal friction was observed at 1% Nano-silica with 0.5% fibre material as shown in Fig. 6. Nano-material produced the viscous gel which improved the cohesion between clay particles and reduced the inter particle spacing. The fibre material improved the frictional as well as tensile strength through efficient bonding with clay particles. Viscous gel formed by Nano-silica adhered to the

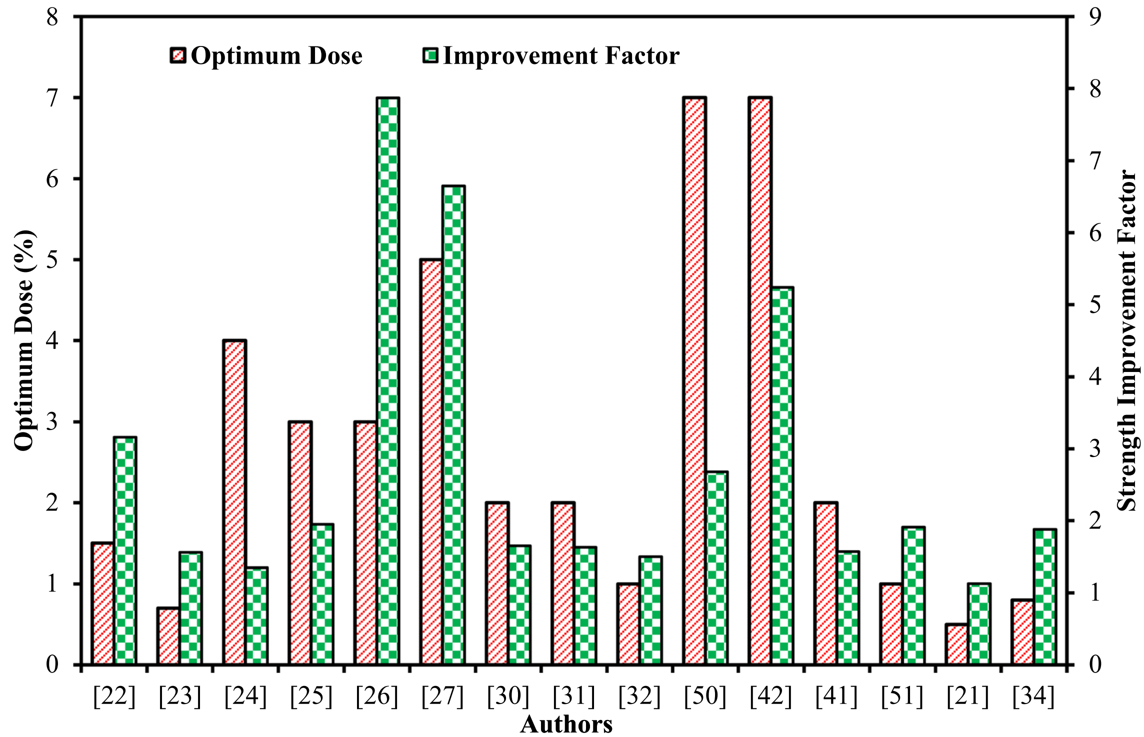


Fig. 5 Variation of Strength improvement factor with optimum dosages suggested by various researchers

surface of fibre material and improved the bonding characteristics between clay and fibre. Similarly, the influence of nano-silica and recycled polyester fibre on loess soil was inspected by Sarli et al. [55]. Alone nano-silica treatment of loess soil resulted to increment in cohesion whereas the frictional property was declined. The mutual combination of nano silica and recycled polyester fibre resulted to increment in both cohesion and frictional parameter of shear strength. The maximum shear strength was obtained with 4% content of nano silica and recycled polyester fibre in proportion of 33 and 50%. The involvement of recycled polyester fibre with nano-silica enhances the interlocking between particles due to higher interfacial contact surface area created by nano-silica particles which led to improvement in the frictional strength as well as cohesion. Ahmadi et al. (2021) [32] documented maximum improvement of 2.47 and 1.36 times in cohesion and friction angle of clay with addition of 1% Nano-silica with 2.5% glass fibres content. Whereas the thermal cycles reduced the shear strength parameters. Nano-silica particles have a higher specific surface area which led to higher affinity towards water absorption and increased the reactivity during hydration process. The nano-silica particles filled the void spaces and increase the interfacial contact surface area which increases the effective stress between the particles. The nano-silica particles reacted with calcium hydroxide which is by-product of cement hydration and transform it to calcium silicate hydrate gel (C–S–H) after cation exchange process. This gel formation replaces the adsorbed water layer found naturally on the surface of clay platelets and provides higher bonding properties between the soil particles by reducing the inter particle spacing. Such improvement in the inter particle bonding improves the frictional resistance along with cohesion and hence led to advance growth in shear strength. The effect of Nano-silica and Nano-silica-based compounds on direct shear strength

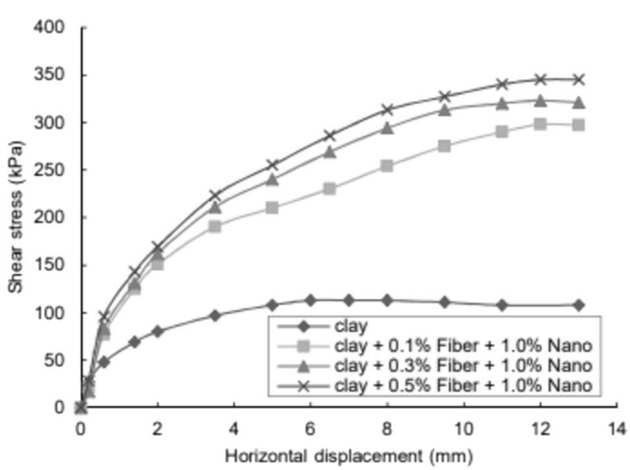


Fig. 6 Variation of shear stress of clay incorporated with Nano-silica and recycled polyester fibre [49]

of soil with key findings and optimum dosage has been summarised in Table 3. Fig. 7 reveals the improvement in cohesion of clayey soil with addition of Nano-silica.

Triaxial Shear Strength

Gao et al. [56] reported increment in the cohesion and angle of internal friction of loessial soil (silty clay) with the incorporation of fly ash (5%, 10%, 15% by soil wt.) and Nano-silica (3 and 5% by wt. of fly ash) as stabilisers. Nano-silica provided denser structure by filling pore spaces between soil and fly ash particles may be reason for observed behaviour. Krishnan et al. [57] analysed the effect of colloidal nano-silica (7.5–30%) on three types of sand classified on the basis of different relative densities (60, 40 and 30%). It was reported that cohesion was improved in all the varieties of sand on increasing dosage of nano silica up to optimum amount of dosage beyond which trend of reduction was observed whereas the friction angle experiences reduction up to similar dosage of colloidal silica and shows incremental trend after attaining the minimal value. The optimum dosage of colloidal nano-silica reduces as the relative density of the sand increases. The optimum dosages of colloidal silica were 10, 11 and 12.5% for sand with 60, 40 and 30% relative densities, respectively. The improved cohesion was due to higher specific surface area and formation of siloxane compounds after ion exchange reactions. Such bond formation was attributed to reduction in the thickness of double water layer or repulsive forces. The improved bonding between particles with the help of gel formation was also responsible for enhanced shear strength. The effect of Nano-silica and Nano-silica-based compounds on triaxial shear strength of soil with key findings and optimum dosage has been summarised in Table 4.

Tensile Strength

In the past, very limited work on the tensile strength of stabilization of soil using Nano-silica and Nano-silica-based compounds was carried out. Chaudhary et al. [34] documented the report of influence of nano silica on split tensile strength property of bentonite clay. It was found that the tensile strength was prominently increased on increasing the nano silica dosage up to 0.6% by dry weight of bentonite clay beyond which trend of strength reduction was obtained on higher dosages such as 0.8 and 1%. Nano-silica particles during hydration phenomenon neutralises the surface charges present naturally on the soil particles which reduce the repulsive forces and increases the interfacial contact surface area between particles which improved the bonding which resulted to increased tensile strength. During the cation exchange process, the nano-silica particles interact with calcium hydroxide compound which is a by-product of cement hydration process in soil and forms new cementitious compounds in the form of calcium silicate hydrate gel. This gel is viscous in nature which fills the nano as well as micro-pores inside the bentonite soil structure and replaces the adsorbed water layer found on the surface of clay platelets. Such gel improves the adhesion and cohesive property between nano-silica and bentonite particles which was responsible improved split tensile strength. The higher dosages of nano-silica deliver the agglomeration of particles due to its higher specific surface area which disturbs the soil matrix by creating unwanted void spaces and thus reduces the interfacial contact surface between particles. This resulted to decline in the tensile strength at higher dosages of nano-silica due to disturbed volumetric stability of the soil matrix.

California Bearing Ratio

This section of the article deals summarises the studies carried out in past on CBR strength behaviour of subgrade weak and soft soils modified with Nano-silica and Nano-silica-based compounds.

Ugwu et al. [58] investigated the treatment of silty sand, Laterite soil and black soil with organosilane compound Nanomaterial (Nano-Z) with concentrations of 1:300, 1:200, 1:150. The inclusion of additive improved the CBR value of the silty sand and laterite soil due to hydrophobic nature of matrix which prevented water from entering inside the layers of soil. Whereas no improvement in CBR value was seen for black soil, the soil matrix formed after inclusion of nano-silica particles reflects hydrophobic nature as compared to natural. The very tiny size of nano-silica particles penetrates inside the pores spaces of soil structure and provide denser and stiffer soil matrix which restricts the penetration of outside water. The filling effect of nano-silica particles improves the density and reduces the plasticity characteristics. The chemical reactions between nano-silica and soil particles during hydrolysis led to formation of extra amount of cementitious compounds which replaces adsorbed water layer naturally present on the surface of soil particles and reduces the thickness of double water layer. This process reduced the repulsive force and introduced the attraction forces between soil particles. The other mechanism which imparts hydrophobicity to the soil matrix is the formation of long chain of strong siloxane bonds (S–O–Si). The hydrophobic layer generates due to formation of these strong siloxane bonds. These bonds are formed from breaking of silnaol bonds (Si–O) during ion exchange mechanism between nano silica and soil particles after hydration process. This siloxane bond formation increases the inter particle bonding and improves the physical and chemical characteristics of soil

Table 3 Effect of Nano-Silica and Nano-Silica-based compounds on direct shear strength of soil

References	Soil type	Dosage of nano additive (%)	Dosage of primary additive (%)	Observation (s)	Optimum dosage of nano-additive (%)	Optimum dosage of primary additive (%)
[49]	Soft clay soil	Nano-Silica: 0.5, 0.7, 1% by wt. of soil	Recycled polyester Fibre: 0.1, 0.3, 0.5% by wt. of soil	Improved strength by 190% at optimum dose of 1% Nano-Silica with 0.3% fibre content	1%	–
[22]	CL	Nano Silica: 0, 0.5, 1, 1.5. 2, 2.5, 3% by dry wt. of soil	Nano Kaolinite: 0, 0.5, 1, 1.5, 2, 2.5, 3% by dry wt. of soil	Cohesion improved and no change in angle of internal friction; Strength improved by 10 times at optimum dose of 1% Nano-kaolinite and 1.5% Nano Silica	1.5%	1%
[23]	Clay	Nano-Silica: 0.5, 0.7, 1% by wt. of parent soil		Both cohesion and friction angle improved but friction angle showed more improvement, shear strength improved by factor of 1.74 at optimum dose of 0.7%	0.7%	–
[53]	Sand-silt mixture soil	Colloidal Nano-Silica: 5, 10, 15%		Cohesion and friction angle was hiked up to 2 and 1.21% than untreated soil which improved the shear strength	–	–
[54]	Poorly graded sand	Nano-Silica fume: 1, 2, 3, 4, 5, 6%	Silica fume: 5, 10, 15, 20, 25%	Nano-Silica fume enhanced both frictional angle, but Silica fume enhanced only cohesion but declined the frictional angle	3%	10%
[55]	Clay	Nano Silica: 2, 4, 6% by weight of soil	Recycled polyester fibre: 2, 4, 6% by weight of soil	Improvement of 51 and 52% in shear strength at 4% dosage for proportions of 33 and 50%, Nano Silica increased the cohesion and decreased the frictional angle whilst fibre increased both the properties	4%	4%
[32]	Clay	Nano-Silica: 0.5, 1, 1.5%		Strength reduction in Nano treated clay was less than untreated clay after thermal cycles	–	–
[51]	Clay	Nano-Silica: 0.5, 1, 1.5%	Glass fibre: 1.5, 2.5, 3.5%	Enhanced the shear strength at dosage of 1% Nano Silica with 2.5% glass fibre, internal friction and cohesion improved by 2.47 and 1.36 times	1%	2.5%

Table 3 (continued)

References	Soil type	Dosage of nano additive (%)	Dosage of primary additive (%)	Observation (s)	Optimum dosage of nano-additive (%)	Optimum dosage of primary additive (%)
[21]	Clay, Sand and Clayey sand	Nano-Silica: 0.3, 0.5 and 0.7%	Cement: 5 and 10%	Cohesion in clayey sand and sand was prominently improved, whereas the frictional angle was slightly reduced Treated clay showed higher improvement in frictional angle than cohesion	0.5%	–
[52]	Sand	Nano-Silica: 1/100, 1/50 and 1/30 concentration		Both friction angle and cohesion increased	1/50	–

matrix. Changizi and Haddad [59] experienced significant improvement in CBR strength of soft clay with the inclusion of Nano silica. An improvement of 76% in the CBR value of clay was observed with 0.7% Nano-content. Whilst marginal increment was noticed on increasing dosage above 0.7% as shown in Fig. 8. So, the optimum content was documented as 0.7%. This behaviour was attributed to the absorbed water by Nano-silica and produced less compressible soil.

Kulkarni and Mandal [60] reported the modification in CBR strength of silty soil with fly ash and organosilane-based Nano-additive with dilution ratio of (1:100), (1:225), (1:400), and (1:600). It was analysed that fly ash and Nano-additive both effectively improved the CBR values. Fly ash alone at 30% replacement of soil showed maximum improvement of 1.11 times. The concentration of 1:100 Nano-additive amplified strength up to 2.34 times than fly ash treated soil. More than 30% Fly ash reduced the strength due to reduced cohesivity. Nano-additive formed strong siloxane bonds after reaction with soil particles by breaking the silica hydroxyl groups (silanol groups) which had higher water absorption tendency. These siloxane bonds had water repellent characteristics and imparted hydrophobic nature to the soil particles by formation of hydrophobic film around the soil grains at molecular level. Fly ash was rich in silica which also enhanced the formation of siloxane bond and provided more compact and denser soil structure with more impermeable and waterproof characteristics. This stronger long chain of alkyl siloxane bond helps in the improvement of CBR bearing strength of the soil. Parsakhoo [33] observed that mixing of Nano-silica and horsetail ash enhanced the CBR bearing strength of both highly compressible and low compressible clayey clays. Maximum CBR strength was attained with 2% Nano-silica with 4% horse tail ash for both CL and CH.

Alireza et al. [61] recorded the influence of lime and Nano-silica on the CBR value of clay. At early age of curing, the improvement in CBR value of clay with the inclusion of Nano-silica was more than lime. 3% Nano-silica and 5% lime gave maximum improvement (21 times) in the CBR value of clay. Babu and Kasetty [62] documented the increased CBR strength of lime and Nano-silica treated expansive soil (CL-ML). Soil was amended with 2–8% lime and 2–6% Nano-silica. The optimum dosage of lime was 6% which provided the maximum strength. Nano-silica enhanced the strength of soil—lime mixture and maximum strength was reported at 6% Nano-silica with 6% lime. The improvement in the strength was due to the higher reactivity of Nano-silica with lime and soil particles. Ghasabkolaei et al. [38] observed significant improvement in CBR strength after Nano-silica treatment of cemented clayey soil. Maximum improvement was noticed at 1.50% Nano-silica content as shown in Fig. 9. Pozzolanic reactions and Nano-filling effect was

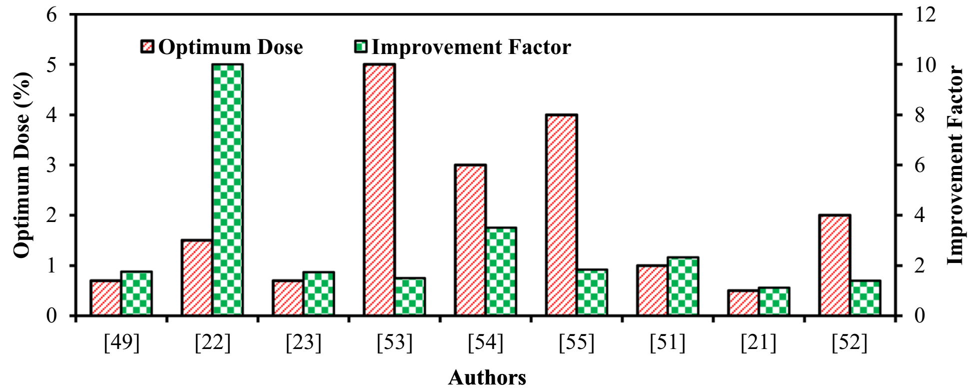


Fig. 7 Improvement in cohesion of clayey soil with addition of Nano-silica

Table 4 Effect of Nano-Silica and Nano-Silica-based compounds on triaxial strength of soil

References	Soil type	Dosage of nano additive (%)	Dosage of primary additive (%)	Observation (s)	Optimum dosage of NANO-additive (%)	Optimum dosage of primary additive (%)
[56]	Silty clay	Nano-Silica: 3 and 5% by wt. of fly ash	Fly ash: 5, 10 and 15%	Enhanced both cohesion and frictional angle	–	–
[57]	Sand	Colloidal Silica: 7.5, 10, 15, 30%	–	Both normalised deviatoric stress and cohesion maximum improved at optimum dose of 10%	10%	–

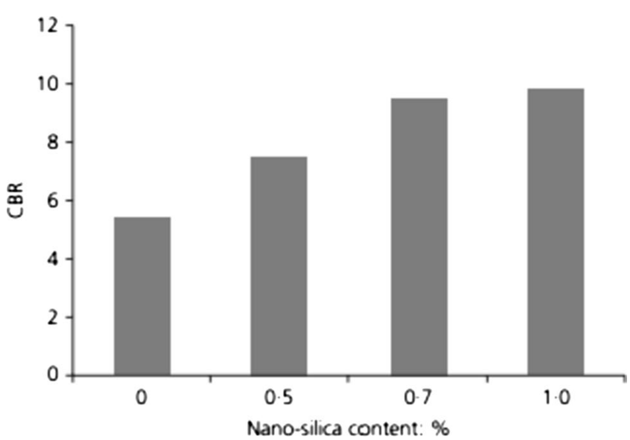


Fig. 8 CBR strength of soft clay with the inclusion of Nano-silica [59]

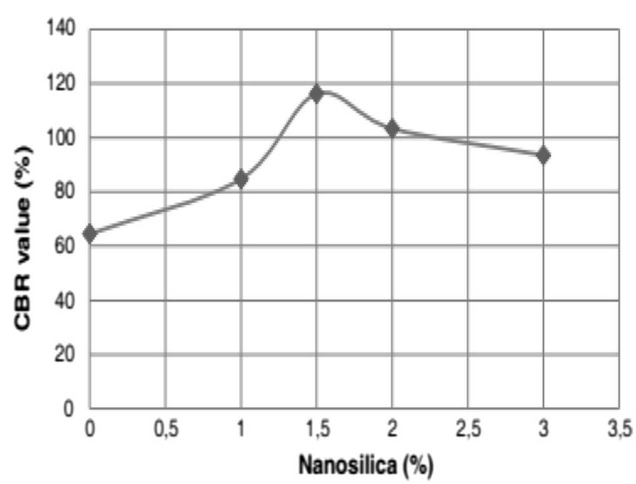


Fig. 9 CBR strength of cemented clayey soil treated with Nano-silica [38]

responsible for strength increment. Kulanthaivel et al. [42] documented that Nano-silica and cement alone did not provide enough enhancement in strength of soil. Whereas the mutual treatment showed significant increment at the optimum dosage content of 2% Nano-silica with 3% white cement with a 31% improvement rate in bearing ratio, this improvement in CBR value was attributed the higher specific surface area of nano-silica particles which reflects quick bonding with soil and cement particles. The formation silicate cementitious materials in the extra amount were responsible for higher bonding between soil particles which improved the CBR strength.

Table 5 Effect of Nano-Silica and Nano-Silica-based compounds on California bearing ratio of soil

References	Soil type	Dosage of nano additive (%)	Dosage of primary additive (%)	Observation (s)	Optimum dosage of nano-additive (%)	Optimum dosage of primary additive (%)
[58]	Laterite soil, clay silty, Black soil	Nano-Z: (1:300), (1:200), (1:150)	–	Increases in Laterite and clay soil but show no changes in black soil	–	–
[61]	CL	Nano-Silica: 1, 3, 5%	Lime: 1, 3, 5, 7%	Enhanced by 21 times when treated mutually by the additives at optimum dose of 5% lime + 3% Nano Silica	3%	5%
[62]	CL-ML type	Nano-Silica: 2, 4, 6% by soil wt	Lime: 2, 4, 6, 8%	Increased, Nano Silica alone had no impact on strength so lime is needed simultaneously	6%	6%
[38]	Clay	Nano-Silica: 1, 1.5, 2, 3%	Cement: 9%	Increased up to 1.5% does after that reduced	1.5%	9%
[60]	Medium expansive silt	Nano-material (orhano silane compound): (1:100), (1:225), (1:400), (1:600) dilution ratio by volume	Fly Ash: 10, 20, 30, 40, 50% by dry wt. of soil	Enhanced, maximum strength obtained at 1:100 Nano + 30% fly ash, Nano material showed more impact than fly ash when treated individually	1:100	30%
[59]	Soft clay	Nano-Silica: 0.5, 0.7, 1%		Increased, dose beyond 0.7% shows marginal changes	0.7%	–
[33]	CL, CH	Nano-Silica: 0.5, 1, 1.5, 2% Curing period: 7, 14, 28 days sample analysis	Horsetail ash: 1, 2, 3 and 4%	Increases up to optimum dose and then reduced	CL: 1% CH: 1.5%	CL: 2% ash CH: 3% ash
[42]	Clay	Nano-Silica: 2, 3, 5, 7, 9%	White cement: 1, 2, 3, 4%	Enhanced by 31% when mutually treated at 2% Nano Silica with 3% white cement	2%	3%

Table 6 Improvement in CBR of soil mixed Nano Silica and other additives

References	Soil Type	Nano-silica/Colloidal silica (optimum dose)	Other additive	Improvement factor
[58]	Silty sand	0.67	–	2.24
[61]	CL	3%	Lime: 5%	21
[62]	CH	6%	Lime: 6%	1.24
[38]	CL	1.5%	Cement: 9%	1.76
[60]	SM	1%	Fly ash: 30%	2.47
[59]	CL, CH	0.7%	–	1.76
[33]	CH	2%	Horsetail ash: 4%	3.13
[42]	Clay	2%	White cement: 3%	2.06

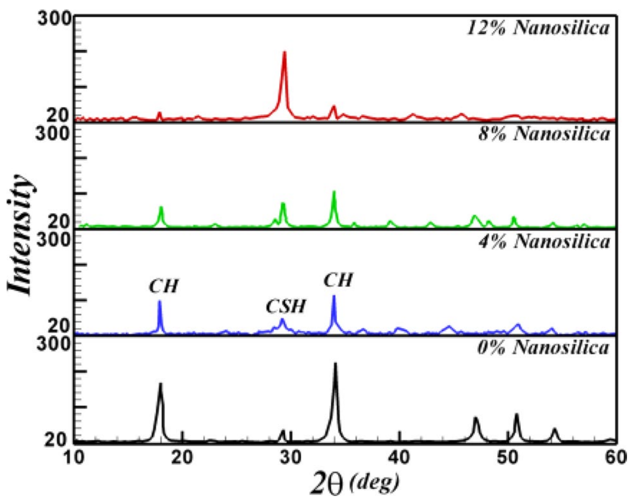


Fig. 10 XRD of sandy soil added with Nano-silica [45]

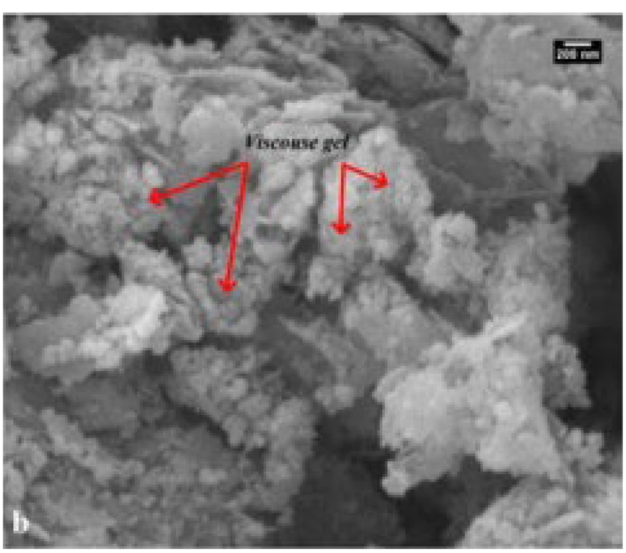


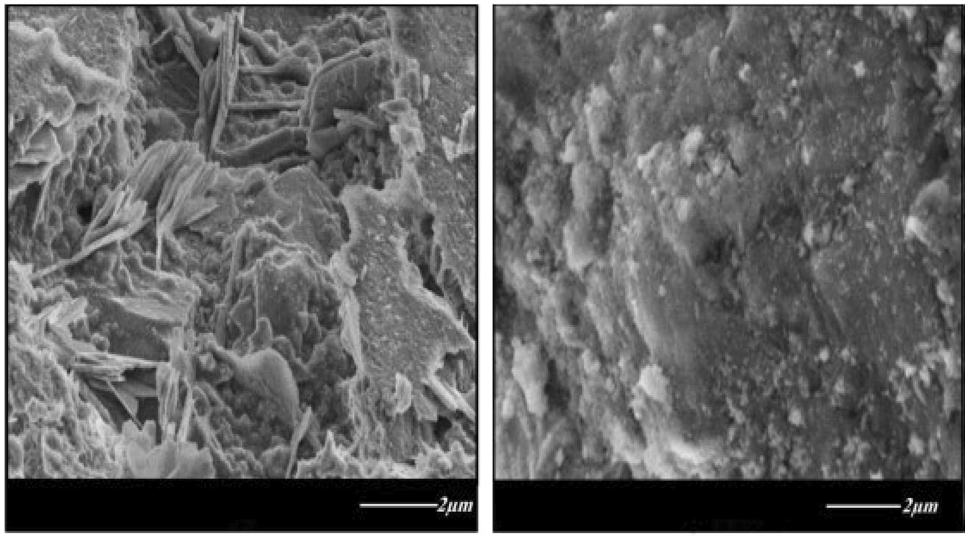
Fig. 11 SEM image of clayey soil stabilized with Nano-silica [32] [12]

The effect of Nano-silica and Nano-silica-based compounds on CBR value of soil with key findings and optimum dosage has been summarised in Table 5. The improvement in CBR of clayey soil mixed Nano-silica and other additives has been summarised in Table 6.

Mineralogy and Morphology Behaviour

The various techniques to study the mineralogical and morphological changes at Nano- and micro-level are available such as Scanning electron microscopy, X-Ray diffraction analysis, Fourier transform infrared radioscopy (FTIR), Atomic force microscope (AFM) and Energy dispersive electroscopy (EDS). This section of the article deals with mineralogy and morphology of Nano-silica and Nano-silica-based compounds stabilised soil to study the changes in the soil structure at micro-level along with the modification in the elemental composition based on past studies.

An increase in the peak intensity of Calcium Silicate Hydrate and reduction in intensity of peak related to Calcium hydroxide was observed by Choobbasti and Kutanaei [45] with the inclusion of 0 and 8% Nano-silica content in clayey soil as shown in Fig. 10. This indicated higher production of C–S–H gel by consumption of Calcium hydroxide crystals after hydration. Higher dosage (12%) of Nano-silica prevented the suitable growth of Calcium hydroxide required for formation of C–S–H gel and thus, reduced the strength. SEM images reported that 8% Nano-silica treatment provided denser and uniform soil matrix due to reduced pores which were filled by viscous gel. Nano-silica enhanced the hydration process due to high specific surface area which provided high reactivity with soil particles. Higher dosage such as 12% Nano-content showed formation of unstable lumps in the structure due to agglomeration of particles caused due to high pozzolanic reactions. The particles stick to each other and formed unstable large size lumps. Similar change in mineralogy and morphology was reported by



(a) (b)

Fig. 12 SEM images of clayey soil **a** cement treated **b** Nano-silica treated [25]

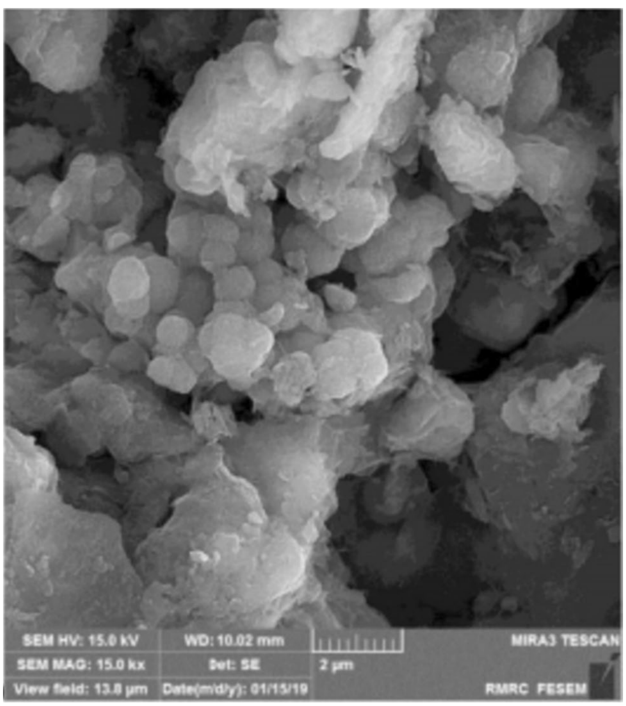


Fig. 13 SEM image of clayey soil stabilized with Nano-silica [30] [32]

Ahmadi and Shafiee [30] and Changizi and Haddad [12] which led to improvement in the cohesion and angle of internal friction between soil particles as shown in Fig. 11. García et al. [25] conducted SEM analysis on Nano-silica amended Lacustrine clay. Images revealed better bonding between the particles after Nano-treatment as shown in Fig. 12. Natural soil showed weak dispersed structure due to presence of double water layer between the clay particles which declined the stiffness and stability of the microstructure. Nano-treated soil resisted the double water layer formation by filled effect by viscous gel in the pore spaces and reduced the inter particle spacing. Higher level of van der wall force of attraction between the particles was reported and imparted more frictional strength. Cheng et al. [36] and Changizi et al. [32] reported the Nano-silica treated clayey soil and Nano-silica treated sand offered better resistance against freeze and thaw cycles, and drying and wetting cycles due to formation of viscous gel and whiskers, which provided better inter particle bonding between the soil particles, respectively, as shown in Fig. 13. Chen et al. [48] reveal denser structure of cemented silty clay after incorporation of nano silica with the help of SEM images due to filling of pore spaces. Formation of more C–S–H colloid was noticed with columnar chalcocite.

Bahmani et al. [37] performed FTIR and SEM on the Nano-silica treated cemented clay. Nano-additive helps in formation of C–S–H gel by reaction with water and Calcium hydroxide during the hydration process of cement. Broad band of siloxane bonds was detected in Nano-treated cemented soil from FTIR as shown in Fig. 14. This gel had filled pores inside the soil and reduced the inter particle spacing which increased the compressive strength up to optimum dosage. Similar behaviour was reported by Ghasabkolaei et al. [38] and Kulanthaivel et al. [42]. Further, Ghasabkolaei et al. [38] performed Atomic force microscopy (AFM) to inspect the surface characteristics of Nano-silica treated cemented clay. Images of AFM revealed reduction in surface roughness with less void ratio and cracks, which indicated

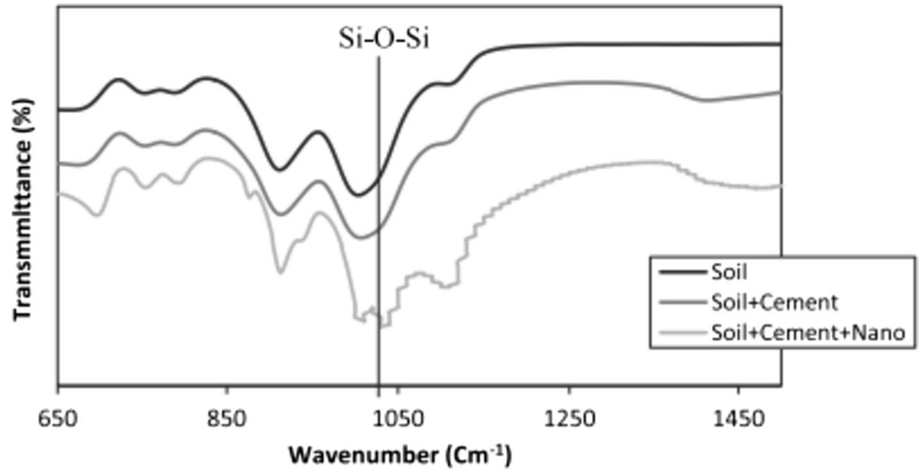


Fig. 14 FTIR results of clayey soil added with Nano-silica [37]

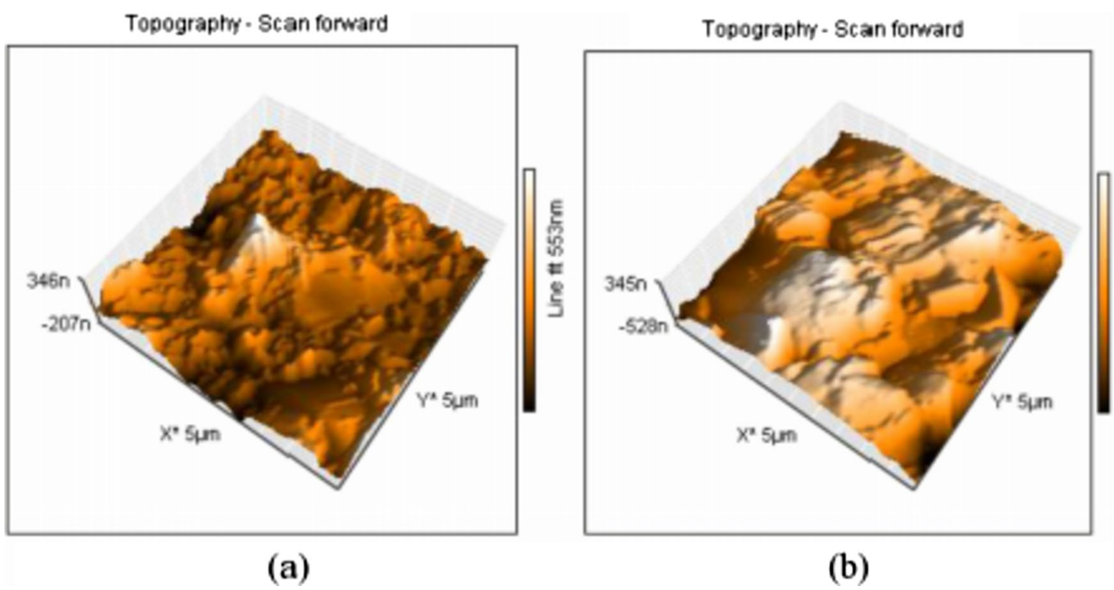


Fig. 15 Atomic force microscopy of clay **a** cement treated **b** Nano-silica treated [38]

more homogeneous soil matrix as shown in Fig. 15. Aksu and Eskisar [21] revealed denser microstructure from SEM images of Nano-silica and cement treated clay, clayey sand and sand. The lesser voids were revealed in the treated soil samples which were filled by the C–S–H gel and Nano-silica particles. The needle like formations and C–S–H gel was detected in the treated soil images. The hexagonal formation denoted the presence of calcium hydroxide. The acceleration of the cement hydration due to higher reactivity of the Nano-particle was responsible for the gel and ettringite formation. Similar behaviour was reported by Luo et al. [47] as well. Tomar et al. [50] investigated the SEM analysis over Nano-silica and PPF treated highly plastic clay and observed that Nano-silica enhanced the bonding between the particles by improving the frictional resistance and adhesion. Nano-silica provided denser and compact soil structure whilst PPF reduced the crack propagation by bridge effect. Fibres act as bridges between the particles to transfer load which prevented the tension cracks.

Conclusion

This review aims to summarise the give detail insight of the strength and microstructural behaviour of Nano-silica and Nano-silica-based compounds treated soil.

- The unconfined compressive strength and California bearing ratio of the different varieties of soil were enhanced after incorporation of suitable amount of Nano-silica and nano-silane compounds. Higher specific surface area of nano-silica particles delivers higher reactivity with soil particles during hydration. During hydration, the formation of viscous gel (C-S-H) after cation exchange phenomenon after suitable period of curing time was responsible for modification in the strength property. The curing period also plays a vital role in gaining strength after Nano-addition due to availability of higher duration of time for pozzolanic reactions. The gel formed fills the void spaces and improves the density as well as compactness of the soil structure and resists deformation at higher loading. Such formation of gel provides better bonding characteristics as compared to adsorbed water found on the surface of soil particles. The effective improvement was observed at lower dosages up to the optimum limit beyond that reduction in the strength was observed. This was due to the agglomeration of very fine particles of nano-silica and soil which disturbs the volumetric stability of the soil matrix.

Also, the reactivity of cement with soil particles was improved by the addition of nano-silica particles due to their higher specific surface area. Nano-silica provides uniform and homogeneous dispersion of cement particles inside the soil structure and thus improved its reactivity which led to formation of extra amount of pozzolanic compounds responsible for further improvement in the strength. The Nano-treatment of soil changed the behaviour of the soil from plastic state to brittle. So, further involvement of different kinds of fibre in nano-treated soil improved the ductility behaviour and found beneficial in reducing crack propagation.

- The addition of nano-silica in soil also modifies the shear strength parameters such as cohesion as well as frictional angle. The split tensile strength of soil was found to be prominently increased with the help of nano-silica due to improved inter particle bonding. On further analysis, it was found that nano-silica increases both cohesion as well as frictional angle in fine grained soil such as clay and silt whereas only cohesive property was improved with no changes or slight reduction in the frictional angle was observed in coarse grained soil such as sand or sand silt mixtures. Absorption of free water by charged small sized Nano-particles provides more hygroscopic properties and higher glutinousness between the soil particles which was responsible for improvement in the cohesive property with no change or slight reduction in the frictional angle. The clayey soil reinforced with cement and fibre shows further improvement in the shear strength parameters after addition of nano-silica compound due to formation of extra amount of cementitious gel. The nano-silica particles improved the interfacial contact bonding between fibre and soil particles due to its higher specific surface area which led to further growth in the shear strength of soil.
- The morphological and mineralogical study reveals formation of uniform and homogeneous soil structure after addition of nano silica compound. The study of scanning electron microscopic and atomic force microscopic images reveals denser and stiffer soil matrix due to filling of void spaces. The mineralogical studies such as X-ray diffraction, Fourier transform infrared radioscopy reveals changes in the mineralogical composition responsible for formation of extra pozzolanic compounds in the form of viscous gel (C–S–H, C–A–S–H) after ion exchange process. Such modification in morphological and mineralogy of soil after incorporation of nano-silica and nano-silane-based compound justifies the behaviour of strength improvement.

Future Scope

Based upon detail review, the authors have observed that insignificant work have been carried on the stabilization of sand using Nano-silica and Nano-silica-based compounds. The usage of chemical surfactants to improve the dispersion efficiency of Nano-particles in the soil is not studied. The inspection of tensile strength of Nano-stabilisation of soil along with fibres such as PPF, Carpet waste fibres is also required for crack mitigation purposes.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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