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Improving the Soil Mechanical Properties of Forest Roads by Combinations of Nano-Silica Materials and Horsetail Ash

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Authors
Parsakhoo A.*[1] *PhD*

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[1]Forestry Department, Forest Science Faculty, Gorgan University of Agricultural Sciences & Natural Resources, Gorgan, Iran

***Correspondence**
Address: Forestry Department, Forest Sciences Faculty, Gorgan University of Agricultural Sciences & Natural Resources, Basij Square, Gorgan, Golestan Province, Iran. Postal Code: 4918943464
Phone: +98 (17) 32427050
Fax: +98 (17) 32427076
aidinparsakhoo@yahoo.com

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ABSTRACT

Aims Fine grained soil shows weak geotechnical properties when they are used in roadbed. The aim of the present study was to assess the efficiency of nano-SiO2 and horsetail ash in improving the mechanical properties of high plastic cohesive soil (CH) and low plastic cohesive soil (CL).

Materials & Methods Soil samples were brought from an earthy bed of proposed roads in Bahramnia Forest, Golestan Province, Iran. Then Atterberg limits, maximum dry density (MDD), unconfined compressive strength (UCS) and California bearing ratio (CBR) tests were conducted on the soil samples treated with 0.5% nano-SiO2+1% ash, 1% nano+2% ash, 1.5% nano+3% ash and 2% nano+4% ash. Analysis was done on 7, 14, and 28-day aged samples. Statistical analysis was done using the SAS 9.4 software to compare means among treatments.

Findings Results showed that liquid limit and plastic limit increased to 56% and 37% for CH and 50% and 32% for CL with increasing the percentage of nano-SiO2 and ash mixture. These changes reduced the plastic index. With the increase in the percentage of additive materials and curing time, the MDD, UCS, and CBR get increases. Dry density decreased by increasing moisture content at the peak state (1.70g cm-3 for CH and 2.03g cm-3 for CL). The nanoash treated CL soil has a higher density than the nanoash treated CH soil.

Conclusion A optimal mixture of 1.5% nano-SiO2+3% horsetail ash and 1% nano-SiO2+2% ash, as well as 28-day curing time, is recommended for the stabilization of CH and CL earthy bed, respectively.

Keywords Plant Ashes; Nanoparticles; Soil Strength; Atterberg limits; Roadbed

CITATION LINKS

[1] Strength properties of soft clay treated with mixture of ... [2] Recent developments of soil ... [3] A review of geotechnical characteristics of nano-additives ... [4] Investigation of nano-clay effect on geotechnical ... [5] A review of stabilization of soils by using ... [6] Influence of nanosilica on compressive strength of ... [7] Influence of nanosized additives on the improvement of ... [8] Effect of nano-SiO2 on the geotechnical properties of ... [9] Effect of lime and fly ash on swell, consolidation and ... [10] Stabilization of residual soil using SiO2 nanoparticles ... [11] Effect of nano silica on swelling, compaction and ... [12] Stabilization treatment of soft subgrade soil by sewage sludge ... [13] Horsetails (Equisetum) as indirect indicators of gold ... [14] On the investigation of the physical properties of ... [15] Standard test methods for laboratory compaction of soil modified ... [16] Calculation of standard proctor density and optimum ... [17] Standard test method for unconfined compressive strength of ... [18] Standard test method for CBR (Calofornia Bearing Ratio) of ... [19] A study on bearing capacity of randomly distributed ... [20] Nanomaterials in ... [21] Stabilization of liquefiable soils using colloidal silica ... [22] Improvement of bearing capacity of soft clay ... [23] Adding calcite and nanocalcite to improving the ... [24] Effect of nano materials on properties of soft ... [25] Assessment of nano-materials on geotechnical properties of ... [26] Assessment of nano-zeolite on soil ... [27] Effect of silica nanoparticles on clay swelling and ... [28] The effect of nanoparticles on geotechnical properties ... [29] Modifying soil shear strength parameters ... [30] Application of nano-material to stabilize a ... [31] Optimum Utilization of Rice Husk Ash for Stabilization of Sub-base Materials in ... [32] Soil stabilization with lime for the construction of forest ... [33] Growth and regeneration of field horsetail ... [34] Experimental study on marl soil stabilization ... [35] The utilization of volcanic ash and high Rusk ash as ... [36] Biological stabilization of a swelling fine-grained ... [37] Sustainable usage of calcium carbide residue for ... [38] Soft expansive soil improvement by eco-friendly waste ... [39] Mechanical and physical characterization of Tabriz ... [40] Stabilization of Urmia Lake peat using natural ... [41] The influence of natural pozzolans structure ...

Introduction

The fine aggregate soil in many parts of the world has created many problems in construction projects, especially road construction [1]. Forest roads have encountered the problem of soils swelling and consequently pavement failure due to high rainfall, high groundwater surface, and unsuitable drainage and also the frequency of clay soils [2, 3]. Therefore, improving geotechnical properties of soil is an important issue that is done using various methods such as biological stabilization of soil, adding lime, ash, cement, nanopolymers, and nanoparticles [4]. The mechanical strength of soil is determined by Atterberg limits, uniaxial compressive strength, triaxial strength, direct shear, proctor dry density, free swell, California bearing ratio and so on [5].

Nowadays, the use of nanomaterials has been highly considered due to their high efficiency in improving the mechanical properties of soils [6]. Nanomaterials are defined as materials with at least one of its dimensions (length, width, and thickness) below 100nm. Due to the large specific surface area, surface charges and sometimes nanoporous, nanoparticles can substantially influence the physical, chemical, and mechanical properties of the soil [7]. Curing time is the length of time (usually from 1 to 4 weeks) needed for additive materials to fully cure and to reach optimum viscosity at a certain temperature. Reducing curing time and increasing the confidence of soil stabilization are the advantages of nanoparticles and plant ashes, which can lead to soil improvement and consolidation of engineering structures, especially in the hard and humid conditions of the forests. Specifications and variables of nanoparticles include purity, average particle size, specific surface area, color, shape, and density. Today, different types of nanoparticles including nano-carbon, nano-Cu, nano-zeolite, nano-clay, nano-SiO_2, and other metal oxides such as nano-MgO and nano-TiO_2 are used for soil stabilization, in which nano-SiO_2 is more important than others [8].

Soil mechanical properties are not improved considerably by adding nano-SiO_2 particles alone [9]. Nano-SiO_2 without other additives not only has little impact on soil swelling but also can increase swelling due to particles softness and more water absorption [10]. Nano-SiO_2 in presence of lime makes a significant decrease in the percentage of swelling of clays with high plasticity so that swelling of the soil after addition of 5% of nano-SiO_2 and 4% of lime decreases from 37.5% to 2.5% within 28 days [11]. In some cases, waste materials including banana leaves ash, rice husk ash, wood ash, and bamboo leaves ash can replace lime [12]. A plant such as Equisetum (horsetail) that accumulates silicon in its tissues will yield more ash per unit of dry weight rather than a plant with lower silicon content. It is known that in *Equisetum arvense L.*, high content of silica can be found in the top part, stem nodes and older plants [13]. The use of nanotechnology in forest engineering science and its application in road materials for improving the physical and mechanical properties increased substantially. A combination of nano and bio-based materials is an appropriate way to reduce soil limitations.

The main purpose of the present study was to investigate the effects of different combinations of nano-SiO_2 and horsetail ash in improving the mechanical properties of high plastic cohesive soil (CH) and low plastic cohesive soil (CL) in a proposed forest road. The effect of curing time was also evaluated in this study.

Materials and Methods

Study area: District two in Dr. Bahramnia Forest with an area of 1,992ha is located from 36°42´30″ to 36°43´30″ N and 54°21´6″ to 54°23´30″ E in Golestan Province of Iran. The bedrock is lime and sandstone with altitude ranging from 500 to 1,935m above sea level. The forest is mixed deciduous which has been established on brown forest soil with mostly sandstone as bedrock silty clay loam texture and worn stones are spread around the region. The climate is moderate and moist. The mean annual precipitation is from 528mm to 817mm which the lowest is in July and August. The total length of proposed forest roads in this district is 28km. Swelling clay soil, stream network, deep trench, erodible area, rocky area, steep terrain, and wetland are the main skidding and road construction constraints in the study area. Therefore, the use of modern technologies such as nanotechnology and bio-based materials is necessary to solve the negative effects of swelling soil and to increase the strength of the sub-base materials of road (Figure 1). Clay with high plasticity (CH) and clay with low plasticity (CL) are two main types of swelling soil which are observed in earthy bed of proposed forest road in the study area. The earthy bed of forest road is a soil beneath road structure after excavation (grade line). The mean of soil depth is this area is 40cm.

Description of soil samples: In this study, the CH and CL soil samples were brought to the laboratory from a swelling earthy bed of proposed forest road in Dr. Bahramnia forestry plan. The soil was air-dried for two weeks and then was sieved. The sieve sizes were 0.015 (No. 40), 0.075, 0.150, 0.60, 2.00, 2.36, 4.00 and 8.00mm. The particle size distribution was obtained from weight of the soil particles retained on each sieve and is usually shown as a graph of "percentage passing by weight" as a function of particle size (Diagram 1). At the next step, the additive materials including nano-SiO_2 and horsetail ash were added to the soil and then sieving operation was done for mechanical analysis (Table 1).

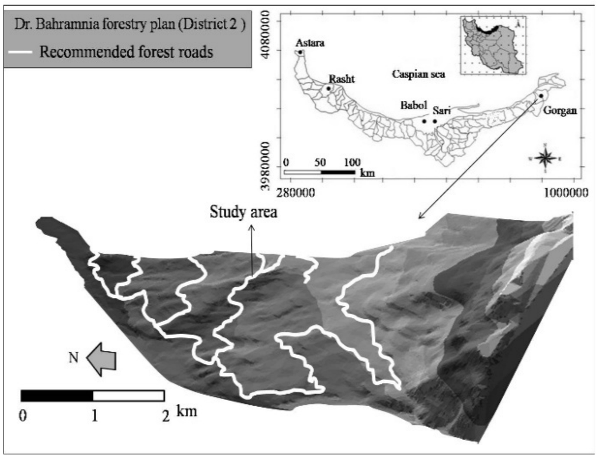

Figure 1) Geographical position of soil sampling areas for treatments

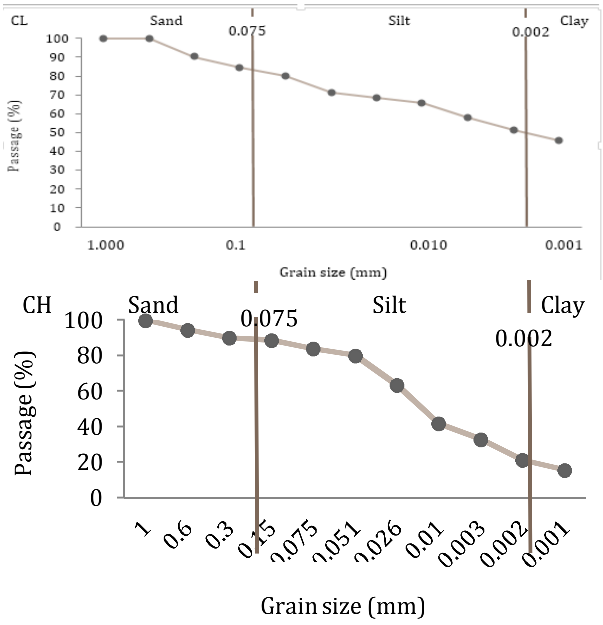

Diagram 1) Soil grain curve for CH and CL

Table 1) Properties of the natural CH and CL soil detected in transport construction

Variables	CH	CL
LL (%)	44.0	41.0
PL (%)	22.0	25.0
PI	22.0	16.0
UCS (KP)	255.0	300.0
MDD (g cm^{-3})	1.59	1.95
OMC (%)	19.0	17.0
CBR (Kg cm^{-2})	8.0	10.0
Organic matter (%)	3.2	4.0
Lime (%)	3.0	4.1

Identification of nano-silica and horsetail ash: Ball-mill extracted nano-SiO_2 was prepared (Zist Tasbit Pars; Iran). The results of the scanning electron microscopy and the chemical properties based on X-ray fluorescence (XRF) analysis have been reported for nano-SiO2 (Table 2 and 3; Figure 2). Samples of *Equisetum arvense L.* (horsetail) have been collected from the roadsides of Dr. Bahramnia Forest in order to produce ash as bio-based stabilizer materials (ash). Nodes of horsetail were separated from stems and then heated in the furnace at 580°C for 2 hours (Figure 3). Some chemical properties of produced ash were reported (Table 4).

Preparation of treatments: First, nano-SiO_2 and horsetail ash were mixed together with different proportions (Table 5). Each mixture was suspended in water (equal to optimum moisture content for better compaction) using ultrasonic dispersion. Then soil samples were treated by each suspension in the mixer device. After 7, 14 and 28 days from the treatment time, soil mechanic tests including Atterberg limits (LL, PL, and PI), MDD, UCS, and CBR was carried out in five replications.

Table 2) Physical properties of nano-SiO_2

Variables	Value
Purity (%)	98.16
Size (nm)	21-33
SSA (m^2 g^{-1})	600-785
Bulk density (g cm^{-3})	<0.10

Table 3) Chemical compound of nano-SiO_2

Element	Value(%)
Al_2O_3	1.2
BaO	0.41
CaO	0.05
K_2O	0.05
MgO	0.04
MnO	0.04
Na_2O	0.02
P_2O_5	0.01
SO_3	0.01
TiO_2	0.01

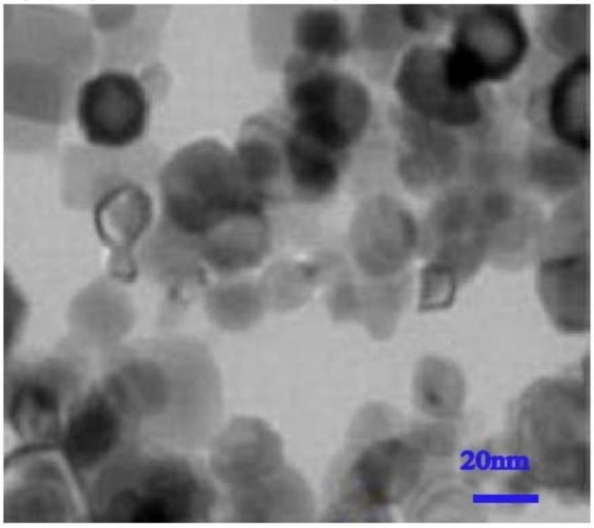

Figure 2) Scanning electron microscopy (SEM) image from nano-SiO_2

Table 4) Chemical compound of horsetails ash

Element	Value(%)
SiO_2	83.5
Al_2O_3	0.51
CaO	6.14
K_2O	3.53
MgO	1.09
Na_2O	0.37
P_2O_5	0.55
SO_3	1.12
Others	3.19

Table 5) Mixtlures of nano-SiO_2 and horsetail ash used in the present study

Mixture No.	Nano-SiO_2 (%)	Horsetail ash (%)
0	0	0
1	0.5	1.0
2	1.0	2.0
3	1.5	3.0
4	2.0	4.0

Soil mechanics tests: In Atterberg limits analysis, LL was determined using the following equation [14]:

$$LL = W_N \times \left[\frac{N}{25}\right]^{0.121} \quad (1)$$

Where N is the number of drops of the cup required to close the groove, W is the soil moisture content (%) that the groove is closed.

Moisture content was determined using the following equation:

$$W = \frac{W_1 - W_2}{W_2 - W_3} \times 100 \quad (2)$$

Where W_1 is the weight of the can (g)+wet soil (g), W_2 is the weight of the can (g)+dry soil (g) and W_3 is the weight of the empty can (g). The tested samples of the soils were oven-dried at 105°C for 24 hours.

The moisture content, as determined in equation 2, when the soil sample is cracking, is the PL. The PI of a soil is the numerical difference between its LL and its PL. It is calculated by the following equation [14]:

$$PI = LL - PL \quad (3)$$

To assess the amount of compaction or MDD and the water content required in the field, the Proctor compaction test (Standard Proctor test) was done on the soil in accordance with ASTM D1557 [15]. The water content, at which the MDD is attained, was obtained from the relationships provided by the test as the following [16]:

$$P_d = \frac{P_W}{\left(\frac{W}{100} + \frac{1}{G_S}\right)} \quad (4)$$

Where P_d is the dry density of soil g cm^{-3}, G_s is specific gravity of the soil being tested (assume 2.70 if not given), P_W is the density of water in g cm^{-3} (approximately 1g cm^{-3}) and W is the moisture content (%). In the Proctor compaction test, the soil was first air-dried and then separated into samples. The water content of each sample was adjusted by adding water. The soil was then placed and compacted in the 4-inch-diameter proctor compaction mould using 25 blows by a 5.5lb standard hammer falling 12 inches. At the end, the sample was removed from mould and the dry density and the water content of the samples were determined for each Proctor compaction test. Then a curve is plotted for the dry density as a function of the water content. From this curve, the MDD can be obtained using OMC.

UCS tests were conducted on 7, 14 and 28-day aged samples. For UCS test, the oven-dried pulverized soils were mixed with the required amount of stabilizer and water. Samples with optimum moisture content and 96% of MDD and diameter of 50mm with the height of 100mm was prepared by static compaction. Then the samples were loaded at a constant strain rate of 1mm min^{-1} for strength test. The UCS values reported are the average of the three tests. The prepared specimens were tested for the UCS based on ASTM D2166 [17].

CBR of a soil is an index which is related to the strength of the soil. Equation 5 represents applied formula for calculating dry unit weight of the soil as the following [18, 19]:

$$Y_d = \frac{Y_t}{1+W} \quad (5)$$

Where Y_d is the dry unit weight of the soil; Y_t is the total unit weight and W is the moisture content (%). In the CBR test, samples of soil were compacted using metal rammer to obtain unit weights both above and below the desired unit weight. After allowing sample to take on water by soaking, or other specified treatments such as curing, each sample was subjected to penetration by a cylindrical rod. Stress versus penetration depth was plotted to determine the CBR for each specimen. The CBR at the specified density was determined from a graph of CBR versus dry unit weight.

Statistical analysis: Statistical analysis was done using the SAS 9.4 software to compare means among treatments. Data were analyzed using ANOVA and Duncan test in terms of soil mechanical properties.

Findings

Atterberg's limits: The results of Atterberg limits test before and after adding nano-SiO_2 and horsetail ash to CH and CL soil were reported (Figure 3). Also, LL (Diagram 2a and d) and PL (Diagram 2b and e), respectively increased to 56% and 37% for CH and 50% and 32% for CL, with the increase of nano-SiO_2 and ash mixture. From the plot, it was deduced that the type of clay influences the Atterberg limits of the soil. The addition of 1.5% nano-SiO_2+3% ash to the CH soil significantly raised the liquid limit from 44% to 51% after 7 days and from 44 to 55 after 28 days. Moreover, the addition of 1% nano-SiO_2+2% ash to the CL soil significantly raised the liquid limit from 44% to 51% after 7 days and from 49% to 52.5% after 28 days. PI which is a composite parameter also showed a remarkable decrease (Diagram 2c and f). Specifically, with the addition of 1.5% nano-SiO_2+3% ash, the PI for the CH soil was reduced from 22 to 18.1% nano-SiO_2+2% ash reduced the PI of the CL soil from 16 to 14. This made CH and CL soil suitable as a sub-base soil. It was reported that sub-base soil with PI greater than 18 are considered marginal to poor sub-base soil.

Figure 3) Horsetail ash production; a) air-dried horsetails, b) separated nodes, c) node chips, d) ash

Maximum Dry Density (MDD) and Optimum Moisture Content (OMC): Adding nano-SiO_2 and horsetail ash had a considerable impact on the density profile. With the increase in the percentage of additive materials, the dry density respectively increased to 1.70g cm^{-3} for CH and 2.03g cm^{-3} for CL. Data from the study revealed that the curing duration exerted a significant influence on the MDD behavior of CH soil mixtures which increased by about 8% as the curing time increased. Moreover, the nanoash treated CL soil has a higher density than the nanoash treated CH soil (Diagram 3a and d; Diagram 3b and e; Diagram 3c and f).

Unconfined Compressive Strength (UCS): The UCS of soil was improved by adding of nano-SiO_2 and horsetail ash. The increase in compressive strength of CH soil ranged from 270Kp for the 0.5% nano-SiO_2+1% ash to 455Kp for the 1.5% nano-SiO_2+3% ash. The untreated CH soil compressive strength was 255Kp. In addition, the increase in compressive strength of CL soil ranged from 340Kp for the 0.5% nano-SiO_2+1% ash to 555Kp for the 1% nano-SiO_2+2% ash. The untreated CL soil compressive strength was 300Kp. The organic matter and lime content in the present studied natural soil were 3.2% and 3%, respectively, which can be important in chemical reaction with additive materials (Table 1). UCS data showed improved strength values of CH soil ranging from 1.61 to 1.78 times higher than the value for specimens tested without any treatment. The strength gains in the CL soils were greater than the CH soil (Diagram 4).

California Bearing Ratio (CBR): CBR test results showed that the CH and CL soil samples containing 2% nano-SiO_2 and 4% horsetail ash had the highest CBR value (25.05% for CH and 27.05% for CL). For the CH soil by adding nano-SiO_2 up to 1.5% and horsetail ash up to 3% and for the CL soil by adding nano-SiO_2 up to 1% and horsetail ash up to 2% no dramatic changes were observed in CBR (Table 6 and 7). CBR value in the CL soils was greater than the CH soil (Diagram 5). Based on reports, a forest road with the thickness of construction 15cm expected to carry vehicles for timber haulage is to be constructed in an area where the CBR value of the subbase is ≥ 30% or 21kg cm^{-2} at penetration of 2.5mm [20-22]. This value was considered in CBR graphical presentation as the horizontal straight line for comparisons. So, in this study, it can be shown that CH and CL soil samples reach demanded CBR at mixture No. 3 (1.5% nano-SiO_2+3% horsetail ash) and mixture No. 2 (1% nano-SiO_2+2% horsetail ash), respectively.

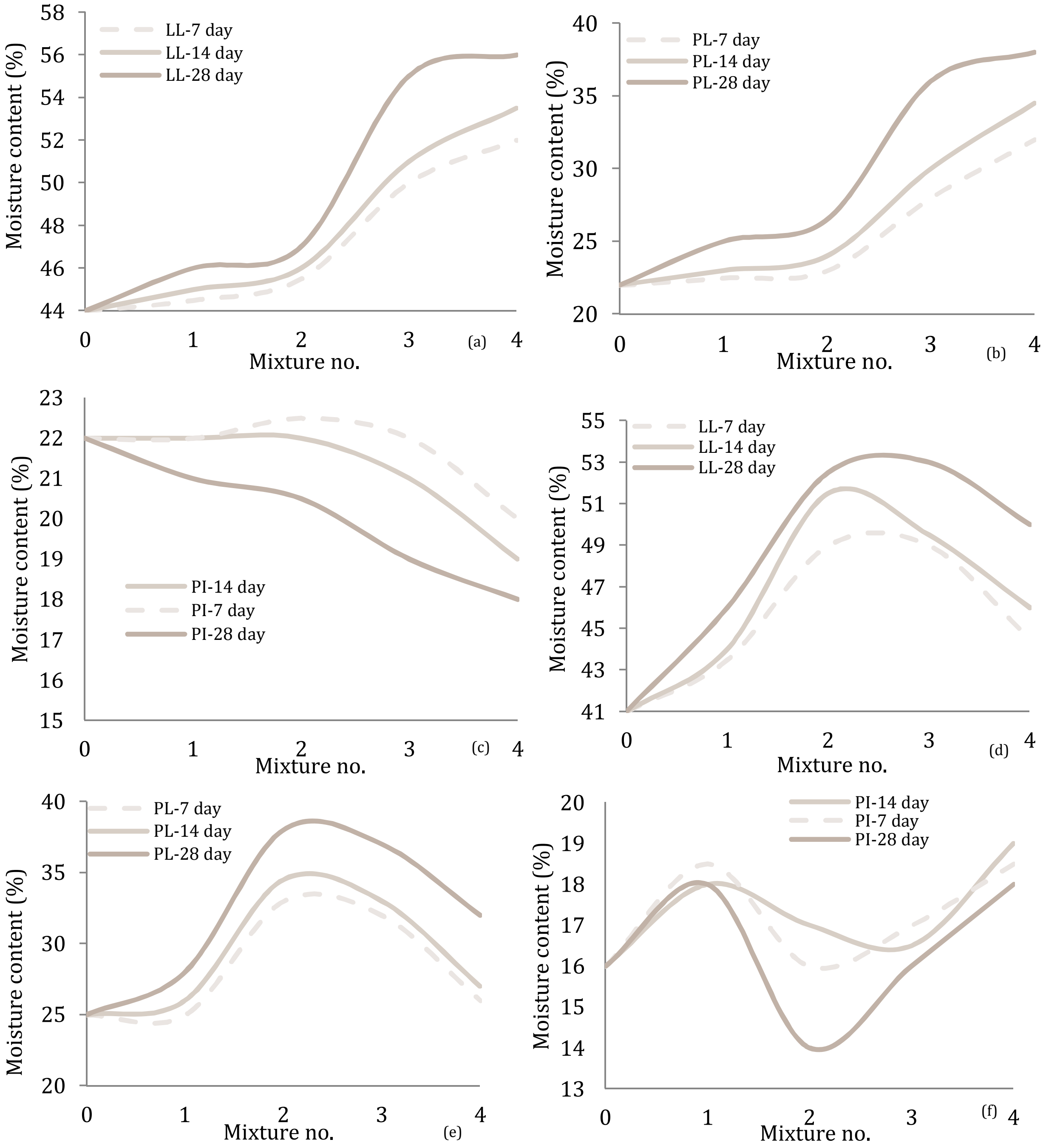

Diagram 2) Influence of nano-SiO_2 and horsetail ash mixtures on liquid limit (LL), plastic limit (PL), and plastic index (PI) in different curing times for (a-c) CH and (d-f) CL soil

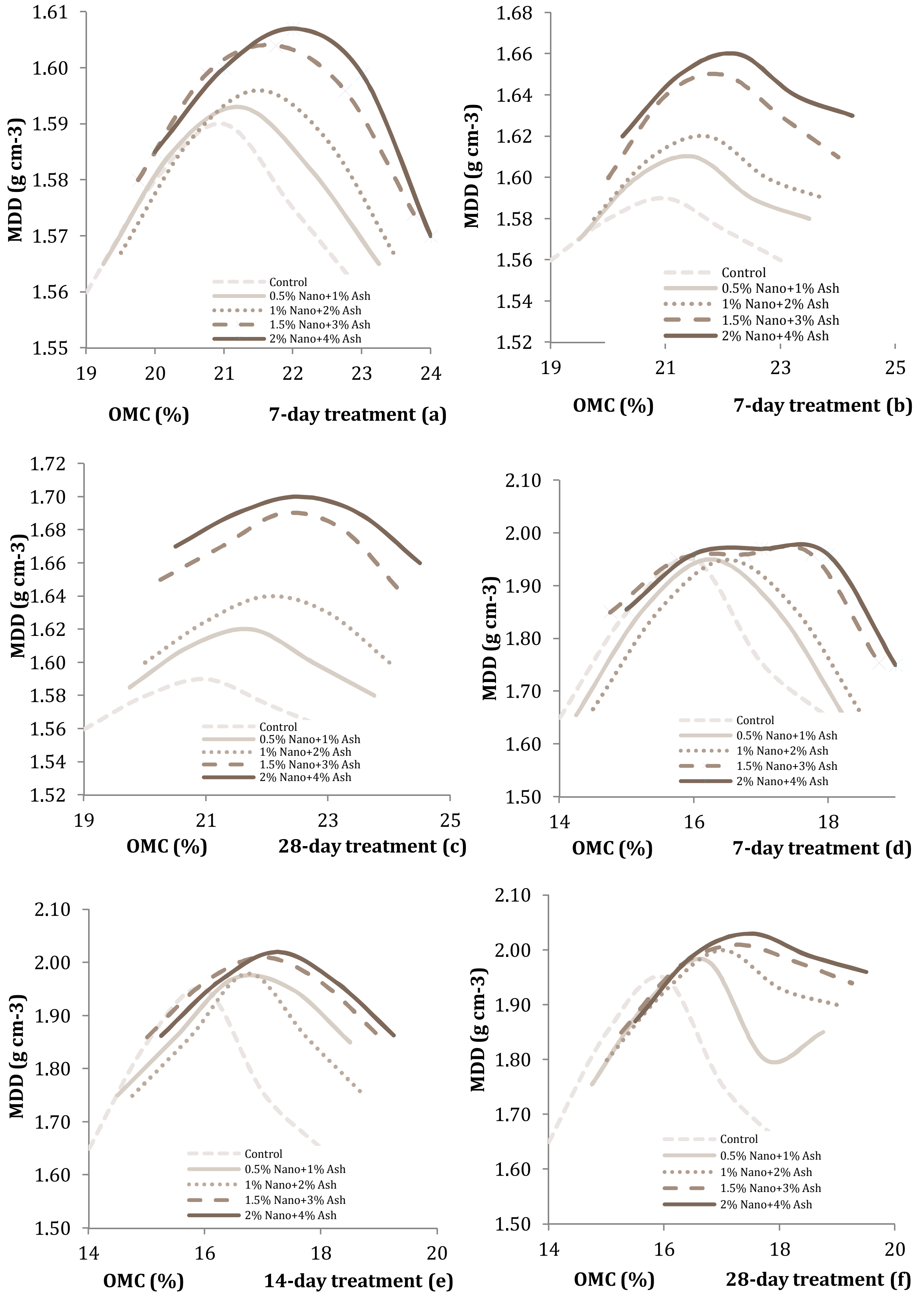

Diagram 3) Influence of nano-SiO_2 and horsetail ash mixtures on dry density and moisture content in different curing times for (a-c) CH and (d-f) CL soil

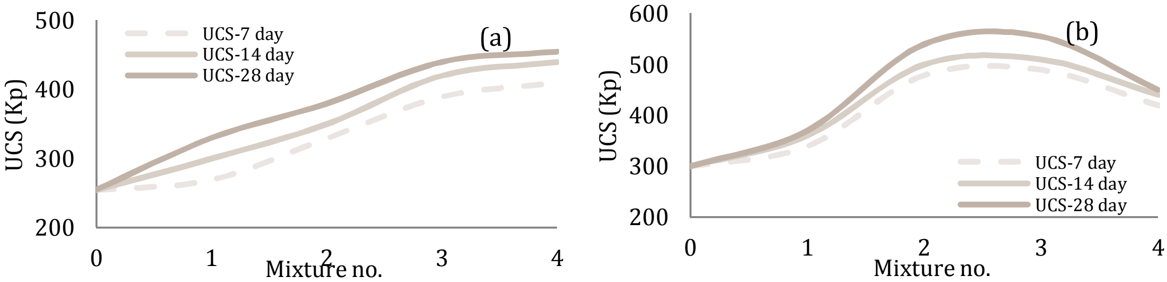

Diagram 4) Influence of nano-SiO$_2$ and horsetail ash mixtures on unconfined compressive strength (UCS) in different curing times for a) CH and b) CL soil

Table 6) Effects of nano-SiO$_2$ and horsetail ash mixtures on improving swelling soil mechanical properties of CH soil

Variable	Control	0.5% Nano+ 1%Ash	1% Nano+ 2% Ash	1.5% Nano+ 3% Ash	2% Nano+ 4% Ash
LL-7 day (%)	44.00^{b}	44.50^{b}	45.50^{b}	50.00^{a}	52.00^{a}
LL-14 day (%)	44.00^{b}	45.00^{b}	46.00^{b}	51.00^{a}	53.50^{a}
LL-28 day (%)	44.00^{b}	46.00^{b}	47.00^{ab}	55.00^{a}	56.00^{a}
PL-7 day (%)	22.00^{b}	22.50^{b}	23.00^{b}	28.00^{a}	32.00^{a}
PL-14 day (%)	22.00^{b}	23.00^{b}	24.00^{b}	30.00^{a}	34.50^{a}
PL-28 day (%)	22.00^{c}	25.00^{b}	26.50^{ab}	37.00^{a}	37.00^{a}
PI-7 day	22.00^{a}	22.00^{a}	22.50^{a}	22.00^{b}	20.00^{b}
PI-14 day	22.00^{a}	22.00^{a}	22.00^{a}	21.00^{b}	19.00^{b}
PI-28 day	22.00^{a}	21.00^{a}	20.50^{a}	18.00^{b}	19.00^{b}
MDD-7 day (g cm^{-3})	1.59^{a}	1.59^{a}	1.59^{a}	1.60^{a}	1.61^{a}
MDD-14 day (g cm^{-3})	1.59^{b}	1.61^{b}	1.62^{b}	1.65^{a}	1.66^{a}
MDD-28 day (g cm^{-3})	1.59^{b}	1.62^{b}	1.64^{b}	1.69^{a}	1.70^{a}
UCS-7 day (Kp)	255.00^{b}	270.00^{b}	330.00^{ab}	390.00^{a}	410.00^{a}
UCS-14 day (Kp)	255.00^{b}	300.00^{b}	350.00^{ab}	420.00^{a}	440.00^{a}
UCS-28 day (Kp)	255.00^{b}	330.00^{b}	380.00^{ab}	455.00^{a}	440.00^{a}
CBR-7 day (Kg cm^{-2})	8.00^{b}	10.50^{b}	13.00^{b}	20.00^{a}	23.00^{a}
CBR-14 day (Kg cm^{-2})	8.00^{b}	11.00^{b}	14.50^{b}	21.00^{a}	24.50^{a}
CBR-28 day (Kg cm^{-2})	8.00^{b}	12.50^{b}	16.00^{b}	22.00^{a}	25.05^{a}

Means followed by different superscript in a row are significantly different ($p<0.05$).

Table 7) Effects of nano-SiO$_2$ and horsetail ash mixtures on improving swelling soil mechanical properties of CL soil

Variable	Control	0.5% Nano+ 1% Ash	1% Nano+ 2% Ash	1.5% Nano+ 3% Ash	2% Nano+ 4% Ash
LL-7 day (%)	41.00^{b}	43.50^{b}	49.00^{a}	49.00^{a}	44.50^{b}
LL-14 day (%)	41.00^{b}	44.00^{b}	50.00^{a}	49.50^{a}	46.00^{b}
LL-28 day (%)	41.00^{b}	46.00^{b}	52.50^{a}	53.00^{a}	50.00^{ab}
PL-7 day (%)	25.00^{b}	25.00^{b}	33.00^{a}	32.00^{a}	26.00^{b}
PL-14 day (%)	25.00^{b}	26.00^{b}	34.50^{a}	33.00^{a}	27.00^{b}
PL-28 day (%)	25.00^{c}	28.00^{b}	38.00^{a}	37.00^{a}	32.00^{ab}
PI-7 day	16.00^{b}	18.50^{a}	16.00^{b}	17.00^{b}	18.50^{a}
PI-14 day	16.00^{b}	18.00^{a}	15.50^{a}	16.50^{b}	19.00^{a}
PI-28 day	16.00^{b}	18.00^{a}	14.00^{c}	16.00^{b}	18.00^{a}
MDD-7 day (g cm^{-3})	1.95^{a}	1.95^{a}	1.95^{a}	1.96^{a}	1.97^{a}
MDD-14 day (g cm^{-3})	1.95^{b}	1.97^{b}	1.98^{b}	2.01^{a}	2.02^{a}
MDD-28 day (g cm^{-3})	1.95^{b}	1.98^{a}	2.00^{a}	2.01^{a}	2.03^{a}
UCS-7 day (Kp)	300.00^{b}	340.00^{b}	480.00^{a}	490.00^{a}	420.00^{ab}
UCS-14 day (Kp)	300.00^{b}	360.00^{b}	500.00^{a}	510.00^{a}	440.00^{ab}
UCS-28 day (Kp)	300.00^{b}	370.00^{b}	555.00^{a}	540.00^{a}	450.00^{ab}
CBR-7 day (Kg cm^{-2})	10.00^{b}	12.50^{b}	22.00^{a}	25.00^{a}	24.00^{a}
CBR-14 day (Kg cm^{-2})	10.00^{b}	13.00^{b}	23.50^{a}	26.00^{a}	26.50^{a}
CBR-28 day (Kg cm^{-2})	10.00^{b}	14.50^{b}	24.00^{a}	27.00^{a}	27.05^{a}

Means followed by different superscript in a row are significantly different ($p<0.05$).

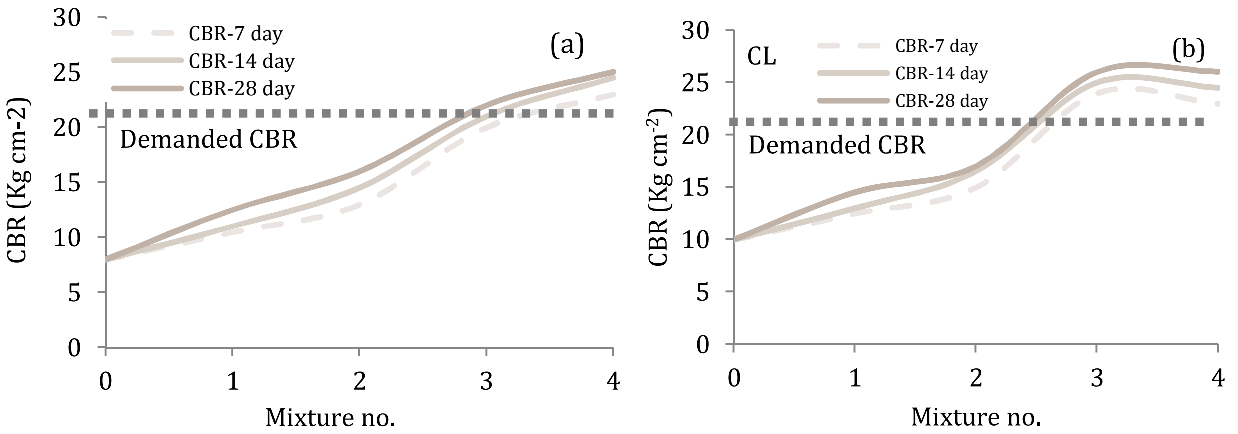

Diagram 5) Influence of nano-SiO_2 and horsetail ash mixtures on California bearing ratio (CBR) in different curing times for a) CH and b) CL soil

Discussion

Results showed that PI for CH and CL soil reduced with the increase of nano-SiO_2 and ash mixture. The water usually enters intraparticle pores through the absorption [9]. Besides, surface charges of nano-SiO_2 on a large specific area is linked to hydrated cations and produced thickness double water layers, resulting in more soil moisture absorption and high Atterberg limits [7]. This process can be a reason of recorded high LL and PL in the present study. In addition, horsetail ash reduces the amount of the clay particles that can freely allow water to enter between the layers causing swelling [8]. In this study, PI-28 day was less than for 7 and 14 days due to more chemical reaction and consequently removing moisture content in curing time. Yazarloo *et al.* [23] investigated the Atterberg limits by adding 3% nano-calcite+0.5% calcite, 4% nano-calcite+1% calcite, 6% nano-calcite+1.5% calcite and 7% nano-calcite+2% calcite. The results indicated that adding calcite led to the decrement of the plastic index and increment of plastic limit in the studied clayey soil.

In this study, with the increase in the percentage of additive materials to CH and CL soil, the moisture content and dry density increased. The nanoash treated CL soil has a higher density than the nanoash treated CH soil. It was confirmed that the shear strength and dry density of the swelling clay soil were improved using nano-SiO_2 particles with the purity of 50% and lime particles (31% Ca and 17% Mg) [7]. The increase in MDD of swelling soil mixed with 2% nano-SiO_2 and 4% ash for standard proctor compaction can be attributed to the presence of large amount of additive materials [22]. Moreover, it is due to the fact that the void within the coarse ash aggregates is being occupied by nano-SiO_2 particles [6]. The increase in OMC is due to the fact that nano-SiO_2 has more specific area and will require more water to be hydrated [24]. This issue causes to decrease in dry density after the peak state. So, the curve can be seen as hyperbolic form [25]. Generally, the results of the compaction tests on the soil agreed with an earlier study conducted on swelling soil by Firoozi *et al.* [26], Pham and Nguyen [27], Priyadharshini and Arumairaj [22] and Nohani and Alimakan [28] but differ in details.

The UCS of CH and CL soil was improved by adding nano-SiO_2 and horsetail ash. Nano-SiO_2 exhibits high pozzolanic activity due to high amount of pure amorphous SiO_2. By adding nano-SiO_2 and plant ash to wet soil, Ca and hydroxide ions of lime in soil decompose and soil pH level increases to 12. Under this condition, the dissolved silicate and Si ions in nano-SiO_2 are combined with hydroxide ions which produces $Si(OH)_3$. These hydroxiades are then combined with Ca ions to shape cementious gels called hydrated calcium silicate. Penetration of these gels into soil pores causes soil strength to increase [26]. In this study, organic matter and lime content of the soil played an important role in chemical reaction. Curing plays an important role in strength development. Properly cured soil samples have an adequate amount of moisture for continued hydration and development of strength. Results of a set of the unconfined compression tests showed that the addition of nano-SiO_2 increases the strength of soil specimens [6, 29].

In a study in north of Iran, adding nano-SiO_2 increased the CBR strength of the soil and soil-lime mixture up to 21 and 7.5 times, respectively. The effects of curing time were also evaluated and the results showed that the CBR strength of the soil-lime mixture increases more rapidly with adding nano-SiO_2 [30]. Nasiri *et al.* [31] and Pereira *et al.* [32] found that the soil CBR increased by adding rice husk ash and lime. The CBR reached its maximum values in the treatment of 4% lime+7% ash. Totally, optimal amounts of mixture for stabilization of CH and CL soil were 1.5% nano-SiO_2+3% horsetail ash and 1% nano-SiO_2+2% horsetail ash, respectively. In the present study area, the occurrence of this plant and its abundance generally was insufficient amount for soil stabilization. The average fresh weight of horsetail which is grown in each square meter of road edge is 1kg. Approximately 2.5kg and 1.7kg Equisetum are necessary for stabilization of one common meter of a forest road with reinforcement 4m wide and 0.1m depth. The genus Equisetum includes about 25 species and is found throughout the world except in Australia and New Zealand [33]. Some species grow in ponds and marshes, some in damp shady places, and some in relatively dry sites [34]. Therefore, on the global scale, the ash of this species can be used in the mixture of nano-SiO_2 in optimum rate detected in the present study to stabilize the CH and CL soil [35]. The nano-SiO_2 works as a binder and generate aggregates in the soil [36, 37]. A wide variety of additives can be used to stabilize swelling soil and improve its geotechnical and engineering properties [38, 39]. Properties of the stabilized soil with these additives depend on the characteristics of both soil and stabilization agent [40]. Natural additives such as ash are local, cost-effective and environmentally friendly additive have been successfully used for soil stabilization [41].

The results of the present study are only based on laboratory experiments, further field tests are required to verify these conclusions.

Conclusion

The addition of silica nanoparticles alone to the soil does not have much impact on soil strength and another activator substance such as ash is needed. Soil plasticity properties have been improved considerably in CH soil samples containing 1.5% nano-SiO_2+3% ash (14% reduction in PI) and for CL soil samples containing 1% nano-SiO_2+2% ash (13% reduction in PI). With the increase in the percentage of nano-SiO_2 and ash mixtures, the dry density, unconfined compressive strength and California bearing ratio of both CH and CL soil get increases. The addition of nano-SiO_2 to samples mixed with ash has increased reactivity rate and hydration process with ash and produced cementitious materials even at an early age (28 days).

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