

## Nano-SiO<sub>2</sub> for efficiency of geotechnical properties of fine soils in mining and civil engineering

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**Abstract.** Taking into account the decreased number of available lands, the construction of structures on soft soil leads towards the development of soil stabilizing models. This study is aimed at studying the decrement of land resources available, and the design of civil engineering structures on soft soils that will develop the soil impact of nano-SiO<sub>2</sub> in the use of clay soil with low liquid limit, in particular shear resistance and unconfined compression. A novel nano-soil stabilizer has been created in this investigation by use of nano-SiO<sub>2</sub> activity and ultrafine features that have enabled cement-based stabilizers to increase their characteristics in broad application possibilities. This research aims to examine the influence on soil engineering, particularly the shear strength of clay soil with a low liquid limit to the effect of adding nano-SiO<sub>2</sub>. Nano-SiO<sub>2</sub> has 3 different percentages combined with soil (i.e., 0.5, 0.7 percent by weight of the parent soil). A direct shear test was used to evaluate the shear strength of the specimen, and then the results were analyzed by Artificial Neural Network (ANN) to increase the accuracy of outcomes. Increased nano-SiO<sub>2</sub> concentration was shown to lead to an increased internal friction angle and cohesiveness on clay soil. The optimal content for nano-SiO<sub>2</sub> is 0.7%. ANN could accurately demonstrate the shear strength percentages in nano-SiO<sub>2</sub> content.

**Keywords:** fly ash (FA); limestone powder (LP); metakaolin (MK); microstructure; self-compacting concrete (SCC) properties; silica fume (SF)

### 1. Introduction

With the continued advancement of worldwide preservation of the environment, sand mining is costly and damages the local ecosystem by excavating mountains and rivers to build concrete projects (Sheng *et al.* 2017, Zhang *et al.* 2020b, Afrazi *et al.* 2021, Ni *et al.* 2021). The waste soil and loose of engineering can again contaminate and difficult to utilize. Moreover, Portland cement and other classic construction materials have extra stone, sand and water quality requirements during mixing, leading to increased technical costs, inadequate soil stabilization, and increased environmental danger in loose plateau and other regions with no rock and sand (Fan *et al.* 2005, Haque *et al.* 2020, Dai *et al.* 2021, Nowroozi *et al.* 2021). In material engineering, there is an urgent need to find low energy

consumption, one type of high strength, and a soil-stabilized environmental material capable of using the water resources and local soil fully and without specific requirements for water quality (Qi *et al.* 2019, 2020, Rouhanifar *et al.* 2019, Rouhanifar *et al.* 2020). Soil Stabilizers have achieved a few research accomplishments in water conservation, road technology and other fields as a flourishing type of environmental protection material in recent years (Phetchuay *et al.* 2016, Coudert *et al.* 2019, Xu *et al.* 2020c, Zhang *et al.* 2021). Many researchers have studied soil stabilizers in the field of study, development and application (Sarkar *et al.* 2019, Javed *et al.* 2020, Akbar *et al.* 2021), (Fan *et al.* 2006) examined the main soil stabilizers' type, features, and stabilizing methods and pointed out that enhancing the stabilizer's strength is vital for future study. The influence of various stabilizers on soil physical and mechanical characteristics was examined by (Shahnavaz *et al.* 2019) and (Zhao *et al.* 2016), although additional study still remains necessary in the consolidation mechanism. In order to change high-cost soils, Sharma *et al.* (2016) utilized a mixture fly ash and slag to alter and increase the capability of soil stabilizers. With the growing demand in

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the field of engineering and protection of the environment for the function of soil stabilization materials, scientists have made great strides to study the strength enhancement of diverse additives in conventional soil stabilizers (Du *et al.* 2016, Xu *et al.* 2020b, Zhang *et al.* 2020a, Yang *et al.* 2021). In recent years, there were substantial accomplishments in research on cement, concrete and other conventional construction materials changed by nano-particles (Roychand *et al.* 2016, Lavergne *et al.* 2019, Feng *et al.* 2020, Xu *et al.* 2020a) as well as positive explosions in soil stabilizer modifications. The impact of nano-SiO<sub>2</sub> on mechanical characteristics and concrete resistance was explored by (Shafiq *et al.* 2019) and (Murthy *et al.* 2019), (Kong *et al.* 2018) discovered that nano-SiO<sub>2</sub> can increase the compressive strength of the soil efficiently and enhances the pore structure. These investigations have enriched soil stabilizer study, but the existing research state has to be further strengthened in comparison to the vast application possibilities demonstrated by soil stabilizers as material to make effective use water resources and soil (Safa *et al.* 2019, Shariati *et al.* 2019a, Suhatriil *et al.* 2019, Zhao *et al.* 2019). New concepts, materials and technologies are urgently needed in additional study to clarify the stability process and enhance the performance of soil stabilizers (Afsar Dizaj *et al.* 2018, Shariati 2020, Shariati *et al.* 2020a, c).

Several stabilization techniques, including construction criteria and mitigation of geographical hazards need to be improved (Shah *et al.* 2016b, Heydari *et al.* 2018, Shariati *et al.* 2020h, Nouri *et al.* 2021). Considerable research has been carried out to increase the loess performance utilizing different stabilizing agents, although much of this work has been on conventional chemical additions (Hosseinpour *et al.* 2018, Naghipour *et al.* 2020, Shariati *et al.* 2020b), Fly ash, lime, and cement are often utilized in the building and geological barriers to more durable loess (Metelková *et al.* 2012, Samah *et al.* 2018, Zhang *et al.* 2018, Shariati *et al.* 2019e, Trung *et al.* 2019a). These chemical additions are often responsible for a short-term physiochemical change, decreasing the water content and increasing the density (Khorramian *et al.* 2016, Khorami *et al.* 2017b, Afshar *et al.* 2020, Shariati *et al.* 2020g). The chemical reactivity makes the long lasting stabilization of pozzolanic and mineralogical and structural changes (Sariosseiri *et al.* 2009, Shahabi *et al.* 2016, Khorami *et al.* 2017a, Shariati *et al.* 2019b). As a result, the mechanical and physical loess produced by these chemical additions is stronger and more effective (Shariati *et al.* 2011a, 2012b, 2013, Shariati 2013, Arabnejad Khanouki *et al.* 2016). However, certain chemical alterations are also produced in treated loess (Sinaei *et al.* 2012, Khorramian *et al.* 2017, Toghrli *et al.* 2017, Zhang *et al.* 2018, Milovancevic *et al.* 2019). These chemical additives usually lead to a significant increase in pH and salinity in alkaline and saline environments (Zia *et al.* 2000, Razavian *et al.* 2020, Rajaei *et al.* 2021, Shariati *et al.* 2021). Carbon emissions and processing costs in different sectors, including lime, cement and fly ash have received high attention in the fields of soil improvement (Phetchuay *et al.* 2016, Shillaber *et al.* 2017, Amran *et al.* 2020, Huseien *et al.* 2021). Therefore, a strong interest in

substituting for soil improvement the commonly used chemical additions with alternative materials was shown (Afshar *et al.* 2020, Siddika *et al.* 2020, Toghrli *et al.* 2020). In soil improvement projects, the interest in alternative materials was raised considerably (Roviello *et al.* 2016, Ziegler *et al.* 2016, Li *et al.* 2021). Due to their unique characteristics, nano-particles have attracted significant attention (Navratilova *et al.* 2015, Judy *et al.* 2016). Prior study has demonstrated that the changes to physical, mechanical and chemical characteristics of nano-particles have been occurred. The influence of nano-particles on clay characteristics was examined by (Taha *et al.* 2012). They discovered that the expanding and shrinking behavior of clays is significantly restricted by nano-clean, nano-alumina, and nano-copper additions not altering their mineralogical characteristics. Research on gamma-aluminum powder and nano-copper oxide for clay has shown poor conductivity and more shrinkage because of smaller pores and more flocculated fabrics (Ng *et al.* 2015, Coe *et al.* 2016). Adding nano-particles can decrease the growth of drying cracks in clays (Taha *et al.* 2012, Changizi *et al.* 2016, Mehrabi *et al.* 2021). In Atterberg clay limits, adding nano-cleaning produces a reduction (Taha *et al.* 2012, Mohammadi *et al.* 2013, Changizi *et al.* 2016). In addition, the strength of the treated clay can evidently be increased with a tiny amount of nano-SiO<sub>2</sub> addition (Changizi *et al.* 2016). Even though sandy and silty soils are utilized in civil engineering, these study works focus on the clays. Several researchers have increased their interest in changing their different characteristics after the inclusion of nano-particles in these soils (Mohammadhassani *et al.* 2014a, Tahmasbi *et al.* 2016, Li *et al.* 2019, Luo *et al.* 2019). Gallagher *et al.* (2002) have shown that colloidal silica obviously reduce the risk of liquefaction of loose sand under seismic loading. In order to minimize liquefaction, Huang *et al.* (2016) examined the effect of laponite on the strength of silty sands. The impacts of nano-SiO<sub>2</sub> on silty soil characteristics were researched by Ren *et al.* (2014). On the basis of laboratory and field research, Tabarsa *et al.* (2018) analyzed the possibility of advancing of soil using nano clay. In general, adding nano-particles lead to greater strength and density in diverse treated soils and reduced conductivity, shrinking and Atterberg limits (Shah *et al.* 2016a, Nosrati *et al.* 2018, Toghrli *et al.* 2018). As alternative additives for soil improvement in the substitution of conventional stabilizing agents, nano-particles have been studied (Shariati *et al.* 2011b, 2011c, Shah *et al.* 2015, Ziaei-Nia *et al.* 2018). However, in real engineering, nano-particles (Fig. 3) can create lower costs than conventional chemicals like concrete and lime (Arabnejad Khanouki *et al.* 2010, 2011, Shariati *et al.* 2012a, Ren *et al.* 2014, Ismail *et al.* 2018). Thus, nano-particles are more advantageous and more likely to be cost-effective additions. The possible benefits in nano-particles would also promise a soil improvement additive (Sinaei *et al.* 2011, Jalali *et al.* 2012, Davoodnabi *et al.* 2019, Xie *et al.* 2019). However, the utilization of nano-particles as a stabilizer of the soil (Fig. 4) is yet unusual (Ng made to use



(a)



(b)



(c)

Fig. 1 Nano-SiO<sub>2</sub> filtration (washing) test a) mixing b) add with cement c) adding Nano-SiO<sub>2</sub>

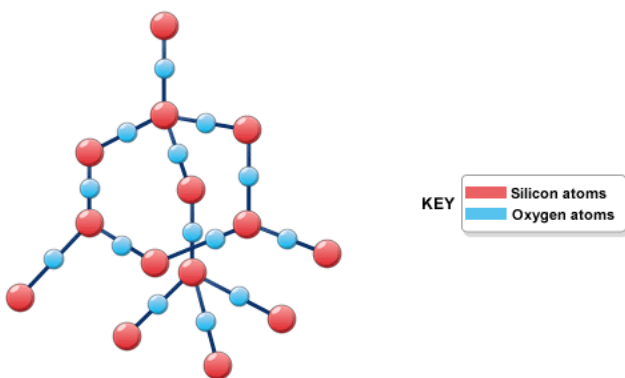


Fig. 2 Nano-SiO<sub>2</sub> nano powder properties

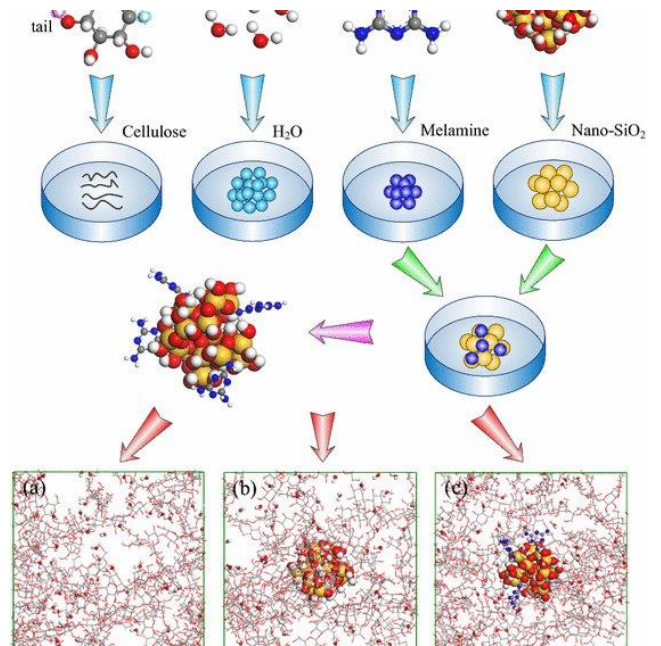


Fig. 3 Nano-SiO<sub>2</sub> particles and water

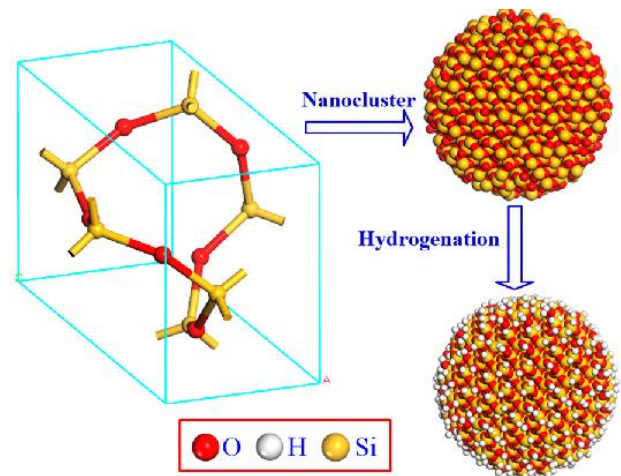


Fig. 4 Nano-SiO<sub>2</sub> particles with water

a nano-particle additive for loess (Tabarsa *et al.* 2018), This article exhibits changes in mechanical, mineralogic and structural characteristics of various nano-SiO<sub>2</sub> concentrations (Fig. 2) and curing days as a result of adding nano-SiO<sub>2</sub>. Unconfined strength, distribution of particle size, SEM imagery and XRD analysis have been examined for a series of tests. The purpose of this work is to gain the development of nano-SiO<sub>2</sub> as well as the complex relationships between macroscopic and microscopic behavior. It is crucial for processes of advancement and practical use in the treatment of loess. Fig. 1 shows nano-SiO<sub>2</sub> filtration (washing) test.

The objective of soil stabilization is to enhance capacity for settlement and deformation to reduce settlement. Soil stabilization techniques may generally be classified into 3 types, i.e., physical, chemical and mechanical approaches. The strength characteristics of the clay soil were improved *et al.* 2015), By now, relatively few attempts have been

Table 1 Physical properties and chemical compositions of loess used in this study

<i>Physical Properties</i>	<i>Value</i>
Specific gravity (Gs)	1.61
Liquid limit (%)	21.98
Plastic limit (%)	12.45
Plasticity index (%)	17.53
Specific surface area (m <sup>2</sup> /g)	17.5
Cation exchange capacity (meq/100 g)	5.3
<i>Chemical compositions (weight%)</i>	
P <sub>2</sub> O <sub>5</sub>	0.15
TiO <sub>2</sub>	0.62
SiO <sub>2</sub>	52.3
Al <sub>2</sub> O <sub>3</sub>	33.81
Fe <sub>2</sub> O <sub>3</sub>	2.57
MnO	0.46
MgO	2.22
CaO	9.21
Na <sub>2</sub> O	2.98
K <sub>2</sub> O	2.34
LOI	5.76
Total	87.54

by the application of fiber, cement and various additives for soil stabilization. Schnaid et al. (2001) found that the cemented soils significantly enhance the elastic module and peak strength, also have a breaker stress/strain behavior with lower effective or greater cement content of the average starting stress. Chemical stabilization using lime or cement is an established technique of improvement of soil performance (Tang et al. 2007),

Hamidi and Hooresfand's work (2013) revealed the added polypropylene fiber to cemented soil to improve peak and residual shear strength and the main stress ratio when fiber content rises. Park (2009) has observed a two-times increase in the axial strain at its top strength compared to the non-fiber-reinforced specimen, due to inclusion of 1% polyvinyl alcohol (PVA) fiber in the cemented sand to 4%. The bridge effect of the fibers may effectively prevent the future development of the soil tension fractures, pointed out by Senol (2012). Many experimental tests have been done on strengthened soil including as unconfined compression, direct shear, triaxial, and CBR tests (Shariati et al. 2012c, 2014, 2017, Changizi et al. 2016, Wei et al. 2018). Tests on clay soils were performed by Fatahi et al. (2013), who discovered that volume changes with increased cement and fiber levels owing to the shrinking of kaolinite and bentonite clays. Nanotechnology has been developed during the last 20 years into an interdisciplinary field of study. Mohammadi and Niazian (2013) revealed that the application of nano-clay considerably enhanced the liquid, plastic, and soil shear strength limits. The soil utilized for the study was categorized as CL under the Unified Soil Classification System.

## 2. Materials and test methods

### 2.1 Materials

Initially, the entire soils were crashed and then the roots, stones, gravel etc were filtered through a 4.75-mm sheet. There was clay and sand in the soil. Nano-SiO<sub>2</sub> was gained from a company in India.

### 2.2 Properties of soil and stabilizer

The soil applied was categorized as CL by Unified Soil Classification System. The SEM picture for nano-SiO<sub>2</sub> is shown in Fig. 1.

### 2.3 Shear test

This test is conducted under fixed and conventional ASTM D3080-90 circumstances. The admixture was poured to three cylindrical layers with a 101.4 mm diameter of 9 116.5 mm in height and was compressed with the aid of a tamping device to achieve desired density. Then the shear ring of 25 mm in length and 69 mm in plan were pushed into the soil mixture by hydraulic jack. The samples were inserted in a shear box and maintained under normal tension for around 24 hours in a water-filled shear box bowl to create the saturated and consolidated samples. The typical stresses were 100, 200 and 300 KPa in the current investigation, whereas the drainage from above and below the cavity was allowed. Then, the sample was sheared under undrained condition when the shear tension was applied. The horizontal movement rate was imposed by 1.25 mm/min. Each combination of mixtures has been tested with three specimens. 36 direct scoring tests of different nano-SiO<sub>2</sub> concentration were done in total. Horizontal distortion up to a total displacement of 13 mm was measured as a result of shear strength. The stress–displacement behavior was plotted from comparing of the shear strength of samples. Fig. 5 shows the saturation stage to wet the sample.

### 2.4 Effect of nano-SiO<sub>2</sub> on the shear parameters of clay

Fig. 4 illustrates the stress-displacement behavior of soils stabilized with different nano-SiO<sub>2</sub> levels and acquired by direct shear testing. The greatest strength of the stabilized land in all the specimens studied in comparison with natural soils occurs at greater horizontal displacement. This figure shows that a raise in nano-SiO<sub>2</sub> and normal stress resulted in a raise of stabilized soil high shear strength. The maximum raising in the peak shear strength is seen at normal stress 300 KPa. By nano-SiO<sub>2</sub> addition, normal stress 300 KPa, the peak shear stress raises by factors 1.33, 1.54, 1.7, respectively, for nano-SiO<sub>2</sub> content of 0.4, 0.5 and 1.0%. From Fig. 8 that the strength curves due to 0.7 and 1.0% nano-SiO<sub>2</sub> are close to each other and the increase in strength for the soil with 1.0% nano-SiO<sub>2</sub> is only about 14% in comparison with the soil 0.7% nano-SiO<sub>2</sub>. Mightily, the optimal nano-SiO<sub>2</sub> content could be

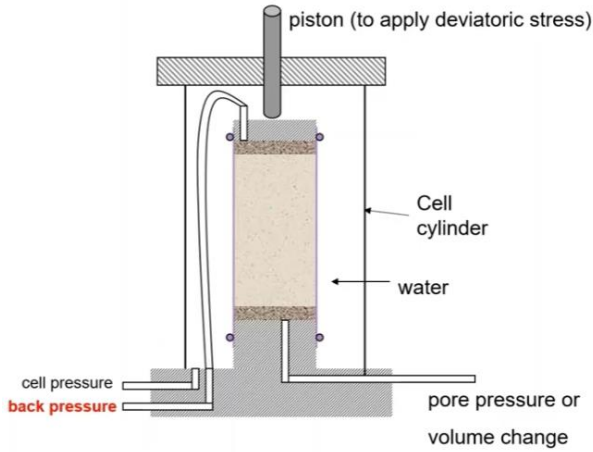


Fig. 5 Saturation stage to wet the sample



(a)



(b)

Fig. 6 Shear test on Nano-SiO<sub>2</sub> Soil

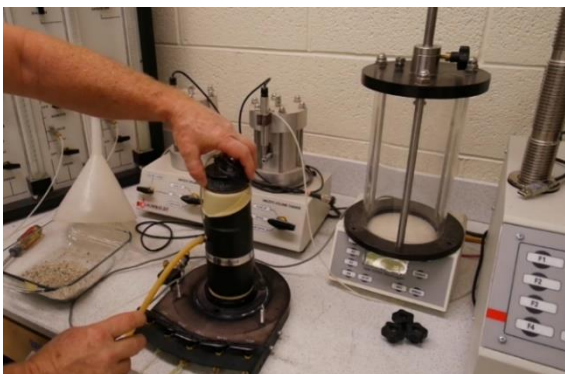
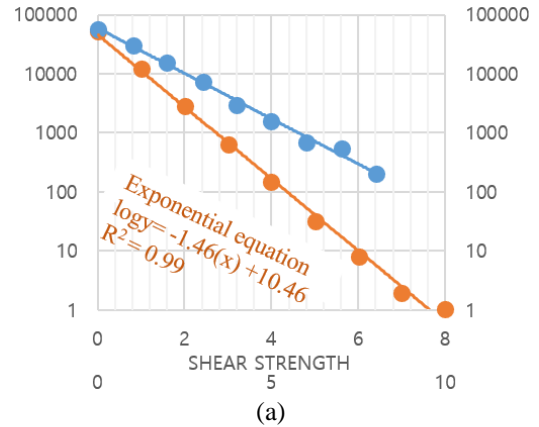
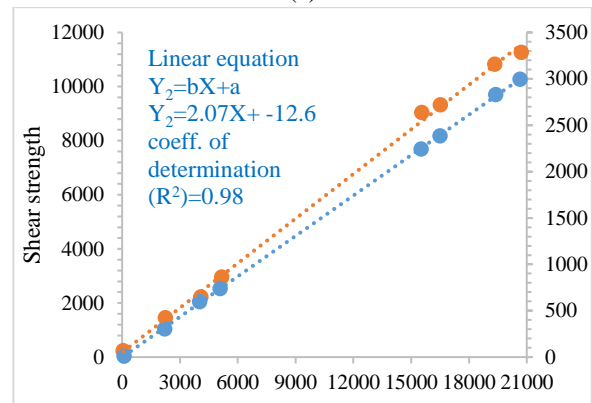


Fig. 7 Testing of shear strength on the specimen



(a)



(b)

Fig. 8 The shear strength of Nano-SiO<sub>2</sub> ratio

0.7%. Fig. 9 shows the failure envelopes corresponding to high shear loads resulting from direct shear testing. Table 1 shows the shear parameters suggesting an increase to the angle of internal friction and cohesiveness of the stabilized soil with increased concentration of nano-SiO<sub>2</sub>. The angles of the friction inside and the cohesiveness are enhanced by 1.52, 1.95, 2.1, 1.11, 1.15, 1.23 and 0.5, 0.7 and 1.0 percent correspondingly. The results reveal that the angle of internal friction with an increase of the nano-SiO<sub>2</sub> content is higher than the cohesion increase; thus, the angle of internal friction of stabilized soil is more effective in increasing soil strength than the cohesion of stabilized soil. Fig. 6 shows the shear test on Nano-SiO<sub>2</sub> Soil, also Fig. 7 indicates testing of shear strength on the specimen.

### 3. Methodology

The ability of experimental techniques in providing accurate results is inevitable, but numerical methods can be more time-saving and cost-effective (Fanaie *et al.* 2017b, Jahanbakhti *et al.* 2017, Asadolahi *et al.* 2020, Partovi *et al.* 2020, Rezaeian *et al.* 2020), For example, Finite Element (FE) is one of the most common methods, which is used for numerical simulation in various areas such as structural analysis, heat transfer, fluid flow, etc. (Fanaie *et al.* 2017a, Al Kajbaf *et al.* 2018, Ghanbari-Ghazijahani *et al.* 2020, Tran *et al.* 2020), On the other hand, Artificial intelligence (AI) algorithms have been employed in recent years to predict and optimize experimental data (Moghadam *et al.*

2010, Mohammadhassani *et al.* 2013, Toghrli *et al.* 2014, 2016, Safa *et al.* 2016, Mansouri *et al.* 2019), In fact, researchers in different fields such as engineering, decision-making, health care and machine vision have applied AI models (Mohammadhassani *et al.* 2014b, Sadeghipour Chahnasir *et al.* 2018, Sedghi *et al.* 2018, Katebi *et al.* 2019, Shariati *et al.* 2019f), The reliability of AI techniques in terms of time, cost and accuracy have been also proved in many papers (Shariati *et al.* 2019c, d, 2020e, 2021a, Trung *et al.* 2019b), Artificial neural network (ANN) performs based on human neurons and is the foundation of artificial intelligence (Fanaie *et al.* 2019, Safa *et al.* 2020, Shariati *et al.* 2020d, f, Yazdani *et al.* 2020),

### 3.1 Statistical data

This research examined the shear strength of soil by adding Nano-SiO<sub>2</sub> to enhance the geotechnical efficiency of soil. To this end, originally 150 data were gathered. The experimental test data were then analyzed by ANN (adding Nano-SiO<sub>2</sub> 2 percent, 2.5 percent, and 3 percent, and water), Two regression indicators of determination coefficient (R<sup>2</sup>) and root mean square (RMSE), Fig. 8 shows the shear strength of Nano-SiO<sub>2</sub> as a) Exponential equation, b) Linear equation.

$$R^2 = \frac{[\sum_{i=1}^N (O_i - \bar{O}) \cdot (P_i - \bar{P})]^2}{\sum_{i=1}^N (O_i - \bar{O}) \cdot \sum_{i=1}^N (P_i - \bar{P})} \quad (1)$$

$$RMSE = \sqrt{\sum_{i=1}^N \frac{1}{N} (O_i - P_i)^2} \quad (2)$$

$O$  = observed values

$N$  = number of training or testing samples

$P$  = predicted values

$\bar{P}$  = predicted values

$P_i$  = predicted values in sample  $i$

$O_i$  = observed values in sample  $i$

$\bar{O}$  = mean of observed variables

## 4. Data preparation

### 4.1. Data distribution pattern

The study utilized ANN to measure precisely the shear strength of the soil added by Nano-SiO<sub>2</sub> to evaluate the effectiveness of the geotechnical characteristics of the soil. The development of the model and its diagrams was shown in Fig. 9. The outcomes of the observation date ANN (horizontal axis) and forecasted data (vertical axis) were seen in the soil shear strength determination during the test phase. The data distribution observed is between 0 and 20, similarly the anticipated values are distributed between 0 and 16. The brown dots are virtually above the blue bold line, which means that the predicted and observed values

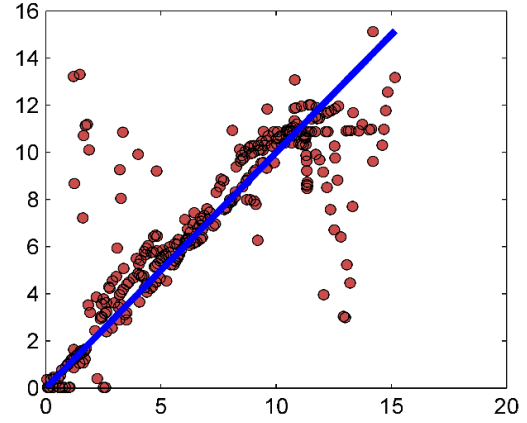


Fig. 9 AI results for shear strength values by ANN (test data)

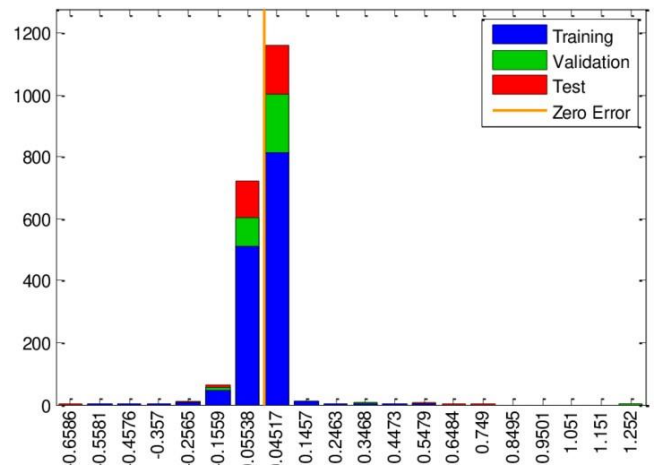


Fig. 10 Error distribution for ANN in test phase

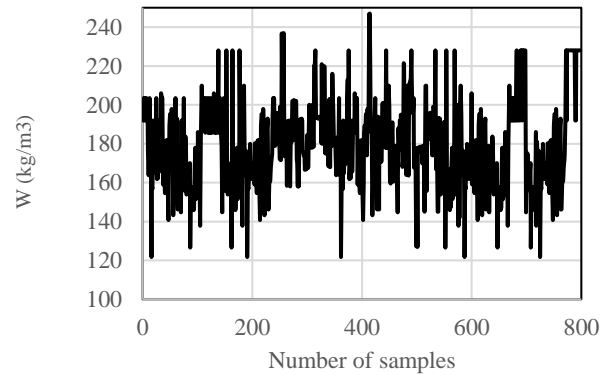


Fig. 11 Observed error values for ANN (test phase)

are well overlapped indicating the precision of ANN model in determining the soils' shear strength while adding nano-SiO<sub>2</sub>. However, there were some differences in data distribution (brown dots), The error distribution is seen in the test-phase of the ANN model in Fig. 10. The horizontal axis represents the error distance between 0.6 and 1.2, while the vertical axis is the data distance number. In addition, the value ( $\sigma$ ) variance is 0.523, whereas the value ( $\mu$ ) mean is -0.111. According to this diagram, the highest error was seen in 0.1 with 1100 data and the lowest error was occurred in 0.7 with roughly 1 data.

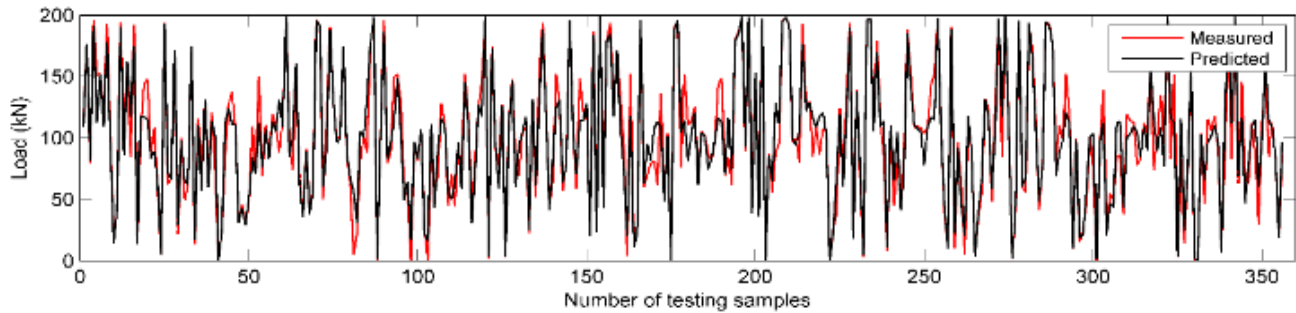


Fig. 12 The assessment of shear strength of Nano-SiO<sub>2</sub> soil by ANN (Test Data)

Table 2 The training and testing phase results of ANN

Training Phase			Testing Phase	
AI Model	RMSE	R <sup>2</sup>	RMSE	R <sup>2</sup>
ANN	0.6754	0.9866	0.6543	0.9765

In Fig.11 (Observed Error Values), the vertical axis is error values and the horizontal axis is the amount of data from 0 to 800.

Fig. 12 displays the observed sample test results on the horizontal axis and the anticipated values on the vertical line. The black line of this figure is shown to be 100% aligned with the real data (ideal form), whereas the radial lines of this study have 10% difference from the black lines (Fig. 12), Any compacting between these two lines implies that our model has the optimal form with the lowest error and highest preciseness, but in our study, this is not the case (very less discrepancy), Comparing the R2 of ANN as 0.9765, the outcomes indicate that the R2 value in ANN is nearer to 1, then ANN could show its best performance (Table 2) in test phase. In analyzing the goal of this study ANN could then demonstrate superior results in predicting the shear strength of Nano-SiO<sub>2</sub> to raise the efficiency of geotechnical properties of Nano-SiO<sub>2</sub> soil.

The respective RMSE and R2 values might describe the properness of the model (Table 2), Naturally, the lowest value for RMSE is 0. Here, the RMSE of ANN is 0.6543 during testing. Consequently, in test phase, ANN would exhibit superior performance with regard to this study as a suitable way of determining the shear strength of Nano-SiO<sub>2</sub> soil in order to increase its geotechnical characteristics.

## 5. Conclusions

This study examined the influence on the shear strength behavior of clay soil by introducing nano-SiO<sub>2</sub>. The impact of nano-SiO<sub>2</sub> on clay soil was investigated based on the data acquired in earlier study from a range of compaction and direct shear tests. The highest shear strength in stabilized soil increases with an increase in nano-SiO<sub>2</sub> concentration so that by adding 0.7 percent nano-SiO<sub>2</sub>, shear stress raised by a factor of 1.74 at normal stress 300 KPa. The increment of shear strength with 1.0% nano-SiO<sub>2</sub> for the soil is only around 14% compared with 0.7% nano-SiO<sub>2</sub> for the soil. When loading tension fractures start to emerge, nano-SiO<sub>2</sub> might lead to a more improvement of ground tension

cracks. Nano-SiO<sub>2</sub> indicates the breakage of stabilized soil increases. On the whole, ANN demonstrated itself to be a successful model for forecasting the shear strength of nano-SiO<sub>2</sub> soil.

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