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Research Article

Assessment of the Effect of Fly Ash and Nanosilica on the Geotechnical Properties of Forest Road Subgrade

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Abstract

This study aims to investigate the effect of nanosilica on the geotechnical parameters of soil stabilized with class C fly ash. For this purpose, the soil of a forest road subgrade in northern Iran was studied, and tests of Atterberg limits, standard compaction, unconfined compressive strength, and California bearing ratio were performed on the soil stabilized with class C fly ash. The optimal amount of fly ash to improve soil strength was found to be 25%. Subsequently, experiments were conducted on soil-fly ash mixtures containing 0.5%, 1%, and 2% nanosilica. The results showed that adding up to 1% nanosilica improves strength, while a further increase in nanosilica leads to a decrease in strength. With 1% nanosilica, the compressive strength and soaked California bearing ratio of the sample containing 25% fly ash increased from 741 kPa to 926 kPa and from 27.4% to 36.2% after 28 days of curing, respectively. The reactivity and high specific surface area of nanosilica lead to accelerated hydration and an increase in cementitious products, which enhance the strength of the samples. The results also show that fly ash and nanosilica improve soil stiffness.

Keywords: *Forest Road Subgrade, Soil Stabilization, Geotechnical Properties, Class C Fly Ash, Nanosilica, Strength Parameters.*

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1. Introduction

Forest roads play a vital role in the successful and sustainable management of forests. Road construction in forests requires special standards and technical considerations, as unauthorized roads can lead to widespread environmental and economic costs. Many of the major damages caused by road construction in the forest are directly related to the soil properties that constitute the subgrade. Therefore, evaluating the mechanical properties of soil is essential for road construction operations and for ensuring stability. Fine-grained soils, which are common in nature, cause problems for construction projects, especially road construction, due to changes in volume and low strength (Ghavami et al., 2021a; Iliyas et al., 2024). Given the presence of these soils in most areas of northern Iran, before implementing construction projects, the soil with the required properties must either be replaced (which is not economically viable) or the existing soil at the construction site must be improved to achieve the necessary engineering properties. One method for improving the strength parameters of soils by altering their physicochemical properties is chemical stabilization using additives. Limitations such as the high cost and environmental problems associated with the production and use of conventional chemical stabilizers, such as Portland cement and lime, have led researchers to consider alternative materials, including industrial wastes like cement kiln dust, fly ash, and ground granulated blast furnace slag (Yoobanpot et al., 2017; Abdila et al., 2021; Turan et al., 2022; Shojamoghadam et al., 2024; Rajaee et al., 2025).

Fly ash consists of tiny ash particles that remain after the combustion of pulverized coal in a furnace at coal-fired power plants. Fly ash, as a waste material, can lead to serious environmental and health problems if not managed properly. However, the chemical compounds present in fly ash and its pozzolanic properties have led to its consideration as a stabilizing agent for base and sub-base materials in road construction (American Coal Ash Association, 2003; Ahmaruzzaman, 2010). According to ASTM C618 (2003), fly ash is divided into class C fly ash (typically containing more than 20% CaO (lime)) and class F fly ash (containing less than 10% CaO) based on its chemical composition. Class C fly ash can be used alone as a stabilizing material due to its high cementitious properties, while class F fly ash is used in soil stabilization with the addition of a cementitious agent such as lime, Portland cement, or cement kiln dust (Arora and Aydilek, 2005; Ghavami and Rajabi, 2021). Turan et al. (2022) conducted unconfined compressive strength and consolidated-undrained triaxial tests on clay soil stabilized with fly ash. They showed that the soil strength parameters increased with the addition of fly ash, and this improvement was greater in soil stabilized with class C fly ash compared to class F fly ash. A similar result has also been reported by Seyrek (2018) and Shirkhanloo et al. (2021). According to laboratory and field tests conducted by Parsons and Kneebone (2005), the addition of class C fly ash to subgrade soils significantly and rapidly improves the strength and stiffness of the pavement section while reducing plasticity and swelling potential. In another study, it was observed that the incorporation of 10% and 18% fly ash into soft fine-grained soils resulted in increases in the California Bearing Ratio (CBR) by factors of 4 and 8, respectively (Edil et al., 2006).

Nanoparticles and nanomaterials, as additives, are often used to improve the properties of materials in various engineering applications, especially in civil engineering (Utsev et al., 2021). Nanomaterials can act as useful fillers due to their very high specific surface area and small particle size, which lead to the fabrication of high-performance cement-based composites (Hosseini et al., 2010; Givi et al., 2013; Arora et al., 2019). An experimental study by Bahmani et al. (2014) confirmed the favorable effects of SiO_2 nanoparticles on the compressibility, hydraulic conductivity, and strength of cement-treated residual soil. Iranpour and Haddad (2016) investigated the effect of various nanomaterials, including nanosilica, nanocopper, nanoclay, and nanoalumina, on soil collapse behavior. The results showed that the combination of soil and nanomaterials is very sensitive, and the positive and negative effects of nanomaterials depend on the amount and type of nanomaterials added to the soil. However, the appropriate amount of nanomaterials can lead to improvements in soil properties. Bhavitha et al. (2024) showed that the unconfined compressive strength (UCS) of lime-stabilized soil increased from 1040 kPa to 1482 kPa with the addition of 3% nano-silica. By investigating the effect of nanosilica on the strength improvement and sustainability of soil stabilized with cement kiln dust, it has been determined that 1% nanosilica is the optimal amount of activator additive used to enhance the geotechnical properties of soil treated with cement kiln dust. Furthermore, due to environmental concerns, no more than 1% nanosilica should be used in the soil-cement kiln dust mixture (Ghavami et al., 2021b). The performance evaluation of nanosilica in fly ash-treated soil also shows significant improvements in the UCS and CBR of the soil-fly ash mixture, as 1.5% nanosilica increased the UCS and soaked CBR of the soil containing 20% fly ash by more than 55% and 40%, respectively (Munda et al., 2022).

A review of the technical literature reveals that nanosilica has been widely utilized in conjunction with chemical additives, including cement and lime. However, there are very few studies on the effectiveness of nanosilica in soil stabilized with industrial waste materials, especially Class C fly ash. Additionally, the combined effect of these additives on forest road subgrade has not been investigated. Therefore, in this study, by conducting Atterberg limits, compaction, UCS, and CBR tests, the optimal amount of class C fly ash is determined for the chemical improvement of the forest road subgrade. Subsequently, the effect of combining nanosilica with the soil-fly ash mixture is investigated.

2. Materials and Methods

The soil used in this study was obtained from the side of a secondary road in the Namkhaneh district of the Kheyrud forest in Nowshahr, northern Iran (Figure 1). First, the soil was completely dried in the open air, and then preliminary characterization tests were conducted according to the standard procedures of the American Society for Testing and Materials (ASTM) to evaluate its geotechnical properties. Figure 2 and Table 1 present the soil particle size distribution and the experimental results, respectively. Based on the Unified Classification System (USCS), the soil used is classified as high-plasticity clay (CH).

The major chemical composition of the examined soil and the class C fly ash used in this study, obtained from X-ray fluorescence (XRF) analysis, is shown in Figure 3. The specific gravity of the fly ash was 2.22. Figure 2 depicts the particle size distribution of fly ash. Nanosilicas used in cement-based materials mainly include 1- pyrogenic nanosilicas, which are produced in powder form through the reaction process of silicon tetrachloride, hydrogen, and

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oxygen in high-temperature furnaces, and 2- nanosilica sols, which are prepared by the nucleation and growth of silica particles in a sodium silicate solution (Bagheri et al., 2013). The nanosilica used as the activator was pyrogenic nanosilica in powder form, manufactured by Evonik Industries (Essen, Germany), with more than 99.8% SiO_2, an average size of 12 nm, and a surface area of 200 ± 25 m²/g.

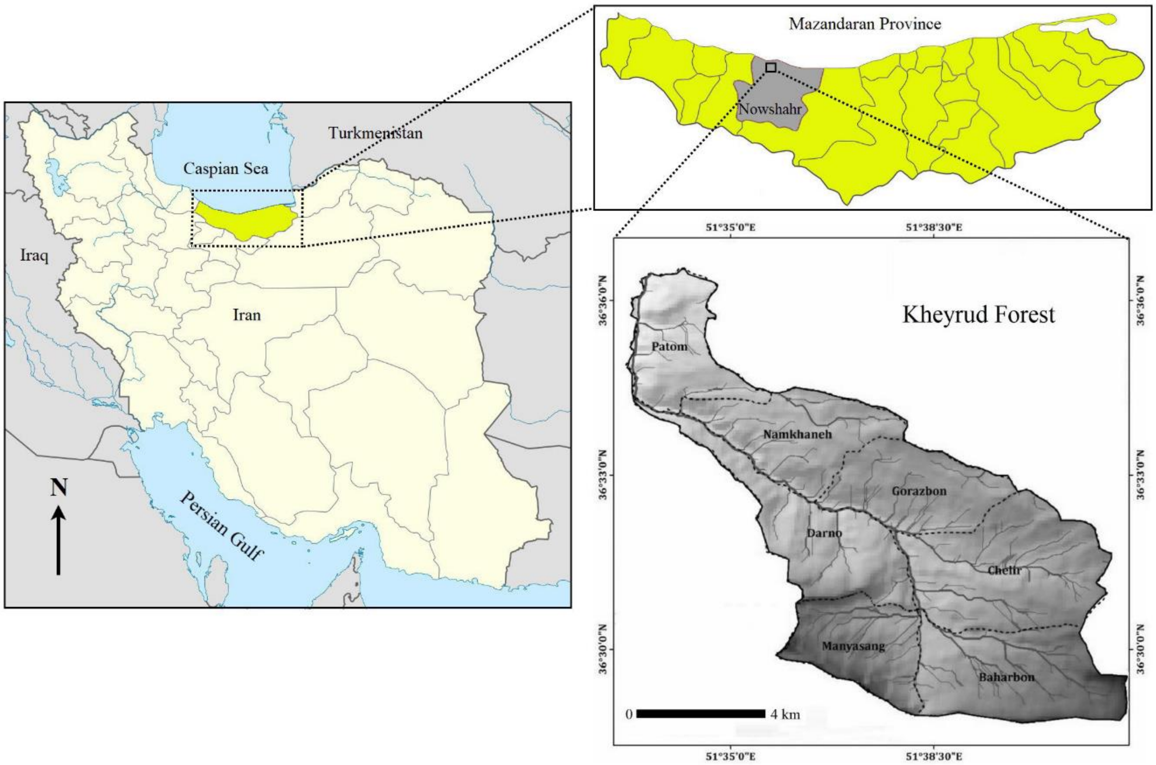

Figure 1. Location of the study area.

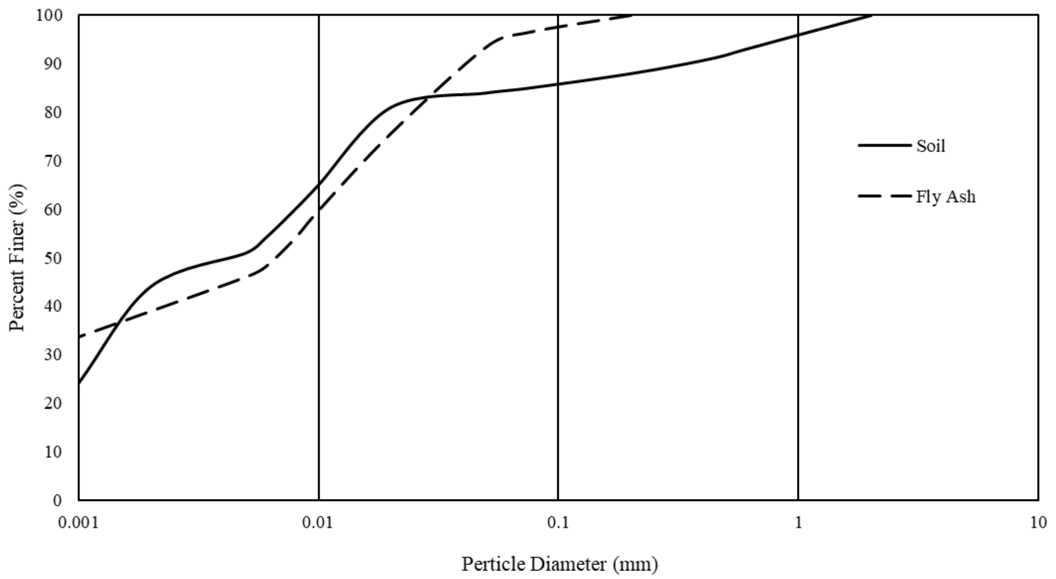

Figure 2. The particle size distribution of soil and fly ash.

Table 1. Geotechnical characteristics of soil.

Properties	Valu	Standard method
Liquid limit (LL), %	58.1	ASTM D4318
Plastic limit (PL), %	25.9	ASTM D4318
Plasticity index (PI), %	32.2	ASTM D4318
Specific Gravity	2.74	ASTM D854
Maximum dry density (MDD), kN/m^3	14	ASTM D698
Optimum moisture content (OMC), %	25.2	ASTM D698
UCS, kPa	56	ASTM D2166
Soaked CBR, %	4.1	ASTM D1883

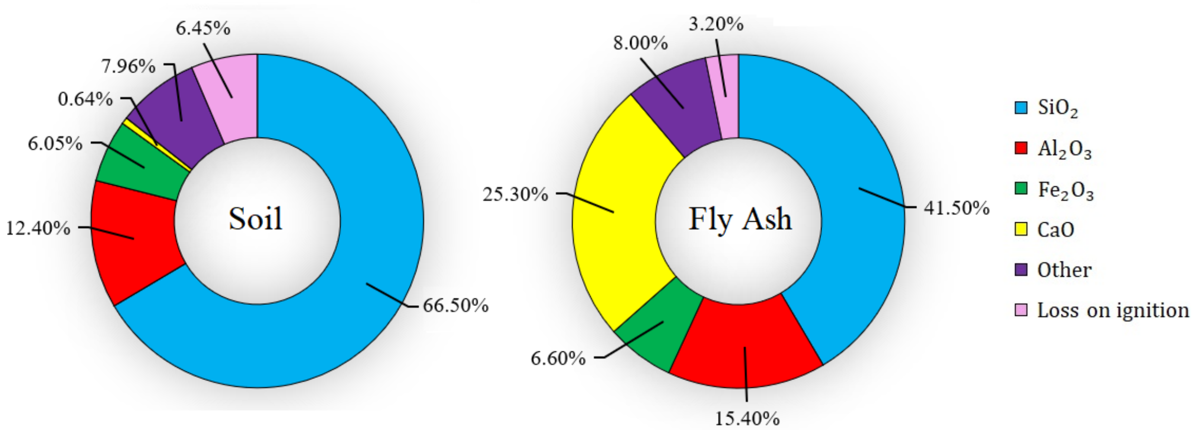

Figure 3. Chemical constituents of materials.

To investigate the effect of fly ash on the geotechnical parameters of the studied soil, 10%, 15%, 20%, 25%, and 30% fly ash (relative to the dry weight of the soil) were added to the soil and mixed homogeneously by hand. One of the important issues in the use of nanoparticles in geotechnical engineering is how to effectively incorporate these materials into the soil. In contrast to additives such as fly ash, which can be mixed manually and homogeneously with soil due to their particle size, fine materials with a high specific surface area, such as silica nanopowder, have significant surface adsorption forces that increase their tendency to clump, making manual mixing impractical. This is because the amount of nanosilica may be higher in one part of the sample and lower in another part. Therefore, nanosilica (in different amounts of 0.5%, 1%, and 2%) was added to the desired amount of water (optimum moisture content), and a homogeneous solution was prepared using an ultrasonic probe. This solution was then sprayed onto the mixture of soil and fly ash. The mixing proportions in the studied samples are presented in Table 2.

The Atterberg limit tests were performed to determine the liquid limit (LL) and plastic limit (PL) of the samples based on ASTM D4318. The plasticity index, which indicates the moisture content at which the soil behaves plastically, is defined as PI = LL-PL. To obtain the optimum moisture content (OMC) and maximum dry density (MDD), the standard compaction test was conducted on the samples following ASTM D698. UCS tests (according to ASTM D2166) were performed on specimens compacted in a cylindrical mold (38 mm in diameter and 76 mm in height) to 100% of the maximum dry density and optimum moisture content obtained from the compaction test. Since a curing time of 28 days is sufficient to form cementitious products, these samples were cured in plastic at 23°C for 28 days (Figure 4a). The test was repeated on three identical samples, and the average UCS value was taken into account. The CBR test was performed in the soaked state according to ASTM D1883. The specimens were prepared in a compaction mold at 100% MDD and OMC, and then placed in a plastic bag for 28 days. The specimens were immersed in water for 96 hours to become saturated (Figure 4b) and were then loaded. The pressure required to penetrate 2.5 mm in the specimen, divided by the pressure required to penetrate 2.5 mm in the standard material, is reported as the CBR value. If the CBR value for 5 mm penetration is greater than the CBR value for 2.5 mm penetration, the CBR value for 5 mm penetration is reported.

Table 2. Mixture proportion.

Sample	Class C Fly Ash	Nanosilica
Soil	0	0
Soil+10%FA	10	0
Soil+15%FA	15	0
Soil+20%FA	20	0
Soil+25%FA	25	0
Soil+30%FA	30	0
Soil+25%FA+0.5%NS	25	0.5
Soil+25%FA+1%NS	25	1
Soil+25%FA+2%NS	25	2

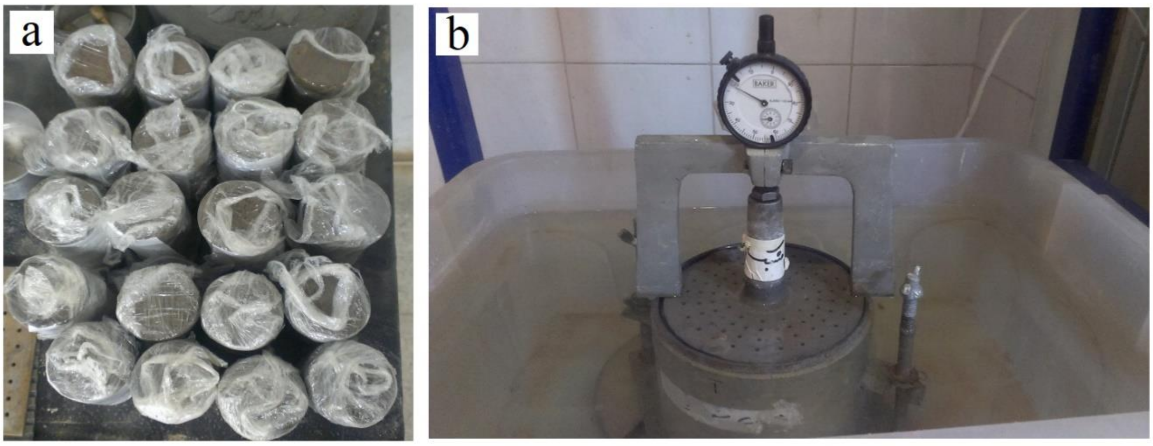

Figure 4. a) Curing the UCS specimens; b) Soaking process in the CBR test.

3. Results and Discussion

3.1. The effect of fly ash on the geotechnical properties of soil

Figure 5 shows the results of Atterberg limit tests on stabilized samples with varying fly ash content. According to the findings of this figure, the liquid limit (LL), plastic limit (PL), and plasticity index (PI) of the soil decrease as the amount of fly ash increases. This decreasing trend continues up to 25% fly ash and then increases slightly as the fly ash content rises to 30%. Flocculation of clay particles in soil can change the soil texture. Therefore, by reducing the effective surface area of the particles, the water required to wet the surface of the particles decreases, resulting in a lower LL. With particle flocculation, they clump together, leading to a decrease in the PI. Cementation reactions in the sample containing fly ash effectively change the soil grain size, which affects the plasticity index (American Coal Ash Association, 2003). 25% fly ash causes the soil plasticity index to decrease from 32.2% to 21.6%. The trend of PI reduction with the addition of class C fly ash has also been reported in previous studies (Bin-Shafique et al., 2010; Nath et al., 2017; Seyrek, 2018).

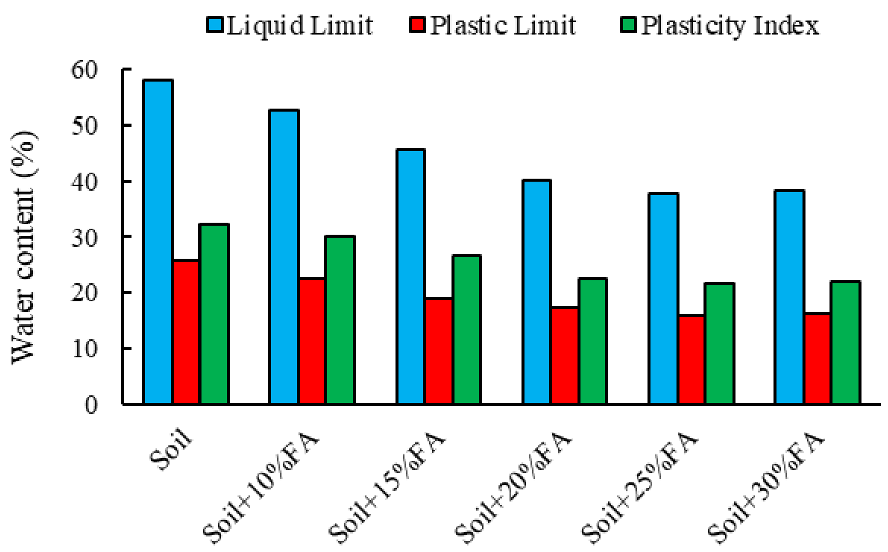

Figure 5. Changes in the Atterberg limits of soil with the addition of fly ash.

The results of the compaction test indicate that with the addition of fly ash, the MDD decreases and the OMC increases (Figure 6). As can be seen, with the addition of 30% fly ash, the MDD of the soil decreases from 14 to 12.2 kN/m^3, and the OMC of the soil increases from 25.2% to 27%. Since the specific gravity (G_s) of fly ash particles is lower than that of soil particles, the MDD of the soil-fly ash mixture decreases with increasing fly ash content. Another reason could be the expenditure of compaction energy to overcome the cementitious bonds between the particles. By adding fly ash to the soil, the flocculation of clay particles leads to the creation of voids among the particles, which, when filled with water, increases the optimal moisture content (Ghavami, 2024; Shojamoghadam et al., 2024). Also, since some of the water is used to create cementitious products, additional moisture is required for the compaction process. The tendency of changes in compaction parameters with the addition of fly ash is similar to the observations of Bin-Shafique et al. (2010), Seyrek (2018), and Turan et al. (2022).

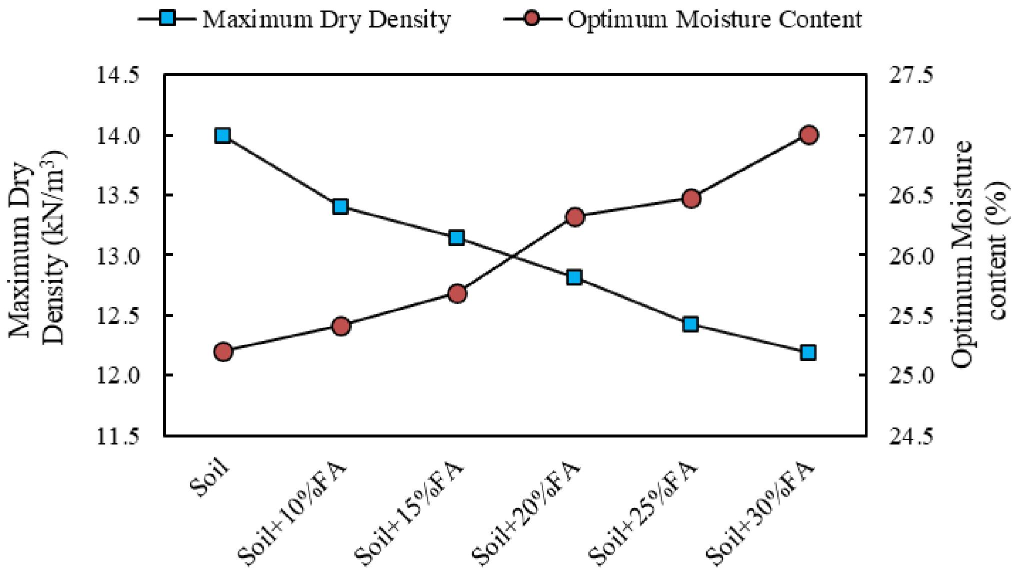

Figure 6. Effect of fly ash on soil compaction parameters.

The effect of fly ash on the UCS of soil is shown in Figure 7. As is clear, the strength increases with the addition of fly ash up to a certain content (25%). The same trend was observed in the results obtained from the California Bearing Ratio test (Figure 8). Other researchers have also determined that the optimal amount of class C fly ash to improve soil engineering properties is between 20% and 25% (Çokça, 2001; Shirkhanloo et al., 2021; Turan et al., 2022; Ghavami, 2024). With 25% class C fly ash, the UCS and the soaked CBR of the soil increased from 56 to 741 kPa and from 4.1 to 27.4, respectively, after 28 days of curing. The increase in soil strength parameters as a result of mixing with class C fly ash has also been confirmed in previous studies (Parsons and Kneebone, 2005; Tastan et al., 2011; Camargo et al., 2013; Yilmaz et al., 2019). The increase in strength is due to pozzolanic reactions and the formation of cementation products, resulting in the bonding of soil particles and stabilizers and filling of empty spaces. When materials containing calcium oxide (CaO) are added to clay, as a result of the interaction between CaO and water, Ca^{2+} and OH^{-} ions enter the soil-stabilizer system.

$$CaO + H_2O \rightarrow Ca(OH)_2 \text{ and } Ca(OH)_2 \rightarrow Ca^{2+} + 2(OH^-)$$

The dissolution of silica and alumina in clay soil and fly ash occurs gradually as a result of the entry of hydroxyl ions into the system. By reacting the calcium and hydroxide released in the above equation with silica and alumina, binding materials such as calcium silicate hydrate (C-S-H), calcium aluminate hydrate (C-A-H), and calcium aluminosilicate hydrate (C-A-S-H) are formed, which facilitate the bonding of soil particles (Ghavami, 2024).

$$Ca^{2+} + 2(OH^-) + SiO_2(\text{Silica in soil and fly ash}) \rightarrow \text{Calcium Silicate Hydrates}$$

$$Ca^{2+} + 2(OH^-) + Al_2O_3(\text{Alumina in soil and fly ash}) \rightarrow \text{Calcium Aluminate Hydrates}$$

$$Ca^{2+} + 2(OH^-) + SiO_2 + Al_2O_3 \rightarrow \text{Calcium AluminoSilicate Hydrate}$$

The stress-strain behavior of fly ash-stabilized soil shows that with the addition of fly ash, the soil behavior becomes more brittle, and failure occurs at lower strains. The secant modulus (E_{50}) values shown in Figure 7 confirm this. E_{50} is a measure of soil stiffness that is equal to the stress-strain slope between zero stress and 50% of the peak axial stress (Ghavami et al., 2018; Krabbenhøft and Wang, 2022).

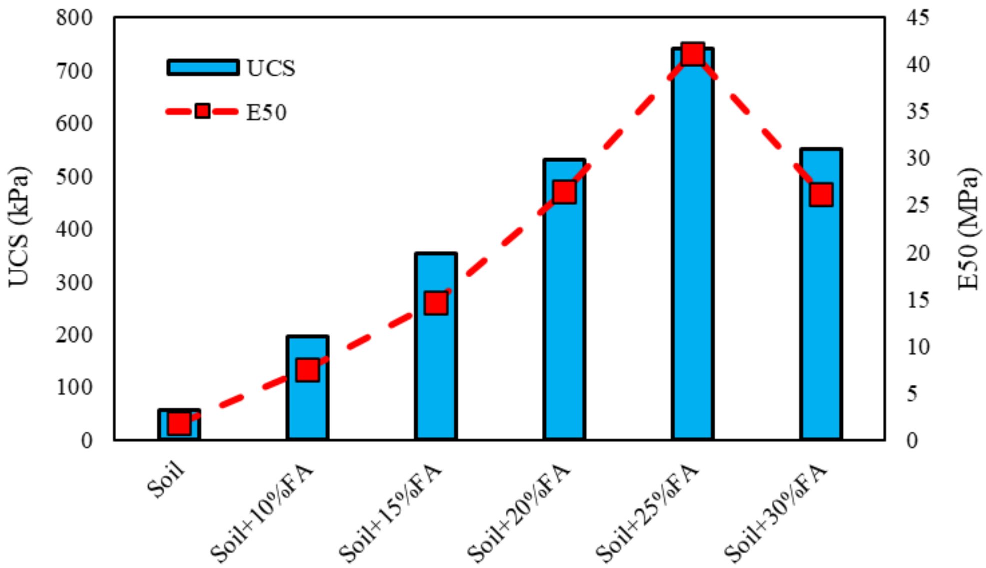

Figure 7. UCS and secant modulus (E_{50}) of stabilized samples with varying fly ash contents.

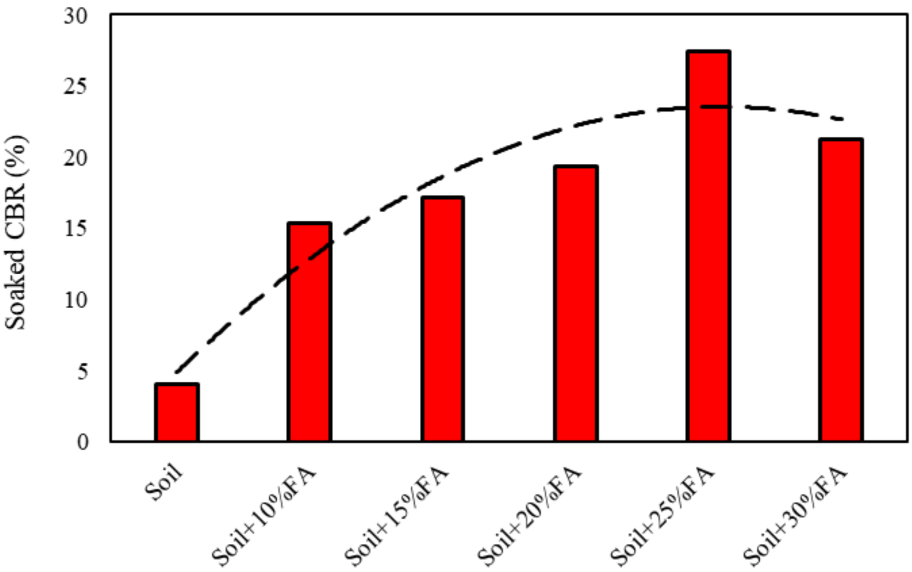

Figure 8. Soaked CBR values of soils with varying fly ash contents.

3.2. The effect of nanosilica on the geotechnical properties of soil stabilized with fly ash

The effect of adding 0.5%, 1%, and 2% nanosilica on the Atterberg limits of soil stabilized with 25% fly ash is shown in Figure 9. The LL slightly increases with increasing nanosilica content, which is consistent with the results of previous studies on the use of nanosilica in chemical soil stabilization (Munda et al., 2021; Aksu and Eskisar, 2023; Wang et al., 2024). However, increasing the nanosilica content has a marginally decreasing effect on the PL. This reduction can be attributed to the nanoparticles being surrounded by a thin layer of water, which results in less water being required to plasticize the matrix (Bahmani et al., 2014; Ghavami et al., 2021b). The increase in the PI of soil stabilized with fly ash, as the nanosilica content increases, is attributed to the high specific surface area of the nanoparticles interacting with the soil matrix particles. With 2% nanosilica, the plasticity index of soil containing 25% fly ash increases from 21.6 to 27.6.

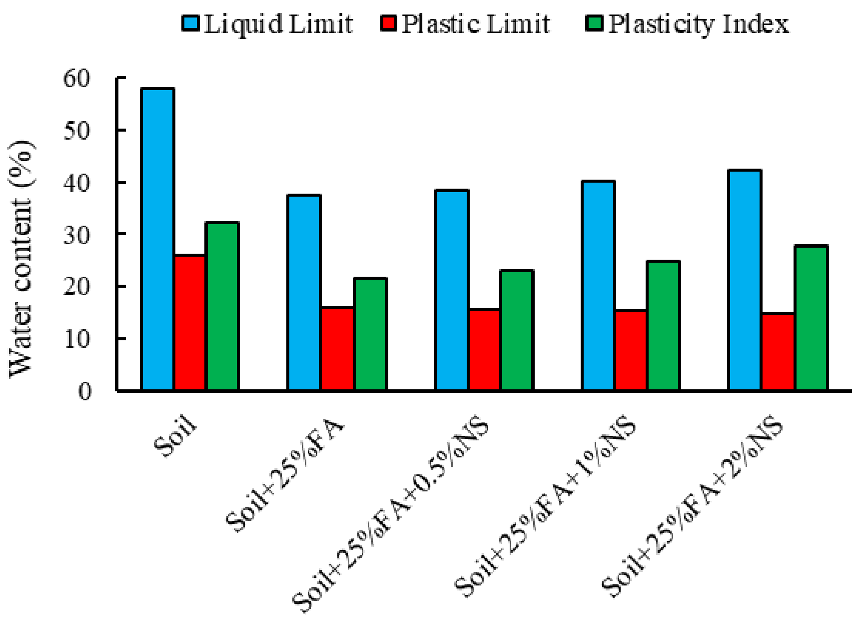

Figure 9. Changes in the Atterberg limits of fly ash-stabilized soil with the addition of nanosilica.

According to the results of the compaction test on samples containing fly ash and nanosilica (Figure 10), it can be observed that nanosilica does not have a significant effect on compaction parameters. The agglomeration of nanopowders and the resulting increase in the number of necks between particles, along with the increasing void ratio of the soil matrix, lead to a slight decrease in the MDD and a slight increase in the OMC. These findings are consistent with the studies conducted by Bahmani et al. (2014) and Karimiazar et al. (2022) regarding the performance of nanosilica in the compaction process.

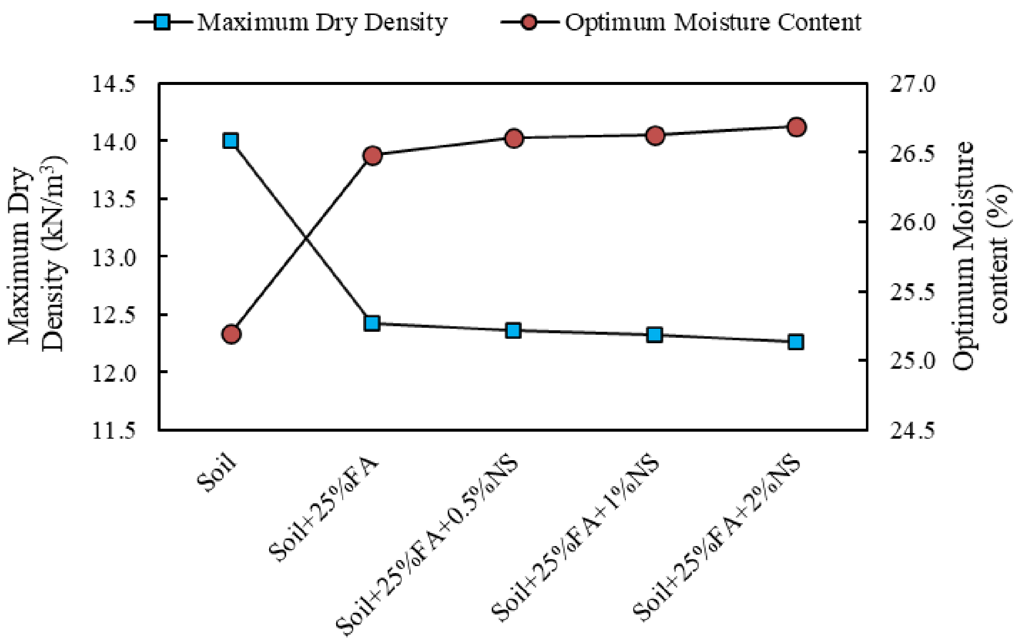

Figure 10. Effect of nanosilica on the compaction parameters of fly ash-stabilized soil.

The average UCS obtained from three test repetitions on samples stabilized with 25% fly ash and 0.5-2% nanosilica is depicted in Figure 11. The strength increases with the addition of nanosilica up to 1%, and above that (2%), it shows lower strength. However, the strength of the sample containing 2% nanosilica is still higher than that of the sample without nanosilica. Munda et al. (2022) have also confirmed that adding nano-silica in a specific amount improves soil strength. With 0.5%, 1%, and 2% nanosilica, the UCS of the soil containing 25% fly ash increases from 741 kPa to 815 kPa, 926 kPa, and 796 kPa, respectively. The rapid consumption of free lime formed during hydration, due to the high reactivity of silica, leads to the production of additional C-S-H gel, which increases the strength of the sample. In addition, nanosilica can accelerate the gelation of the cement products described in the previous section due to its high specific surface area. High content of nanosilica causes dispersion problems due to the agglomeration of excessive amounts of nanoparticles. Nanoparticles also act as fillers to fill the pores of the soil, which stops the hydration process and, thus, reduces strength. As can be seen from Figure 12, the results of the soaked CBR test are consistent with those of the UCS test. A CBR value of 4.1 for the subgrade soil indicates that the soil is weak. The guidelines emphasize developing a subgrade CBR of at least 10 because, with a subgrade strength of less than 10, the subbase materials will deform under traffic loads (Schaefer et al., 2008). 1% nanosilica increases the CBR of a soil containing 25% fly ash by 1.3 times, reaching approximately 36%, which indicates that it can even be used for the subbase course, as the minimum acceptable CBR for a stabilized subbase is 30% (Iran Highway Asphalt Paving Code Number 234, 2010). The secant modulus obtained from the stress-strain curves of samples containing nanosilica shows an increase in the stiffness of these samples (Figure 11). Similar to the effectiveness described for nanosilica in soil containing fly ash, the improved strength of soils stabilized with other chemical additives, such as cement, lime, and cement kiln dust, has also been reported (Bahmani et al., 2014; Ghavmi et al., 2021b; Bhavitha et al., 2024).

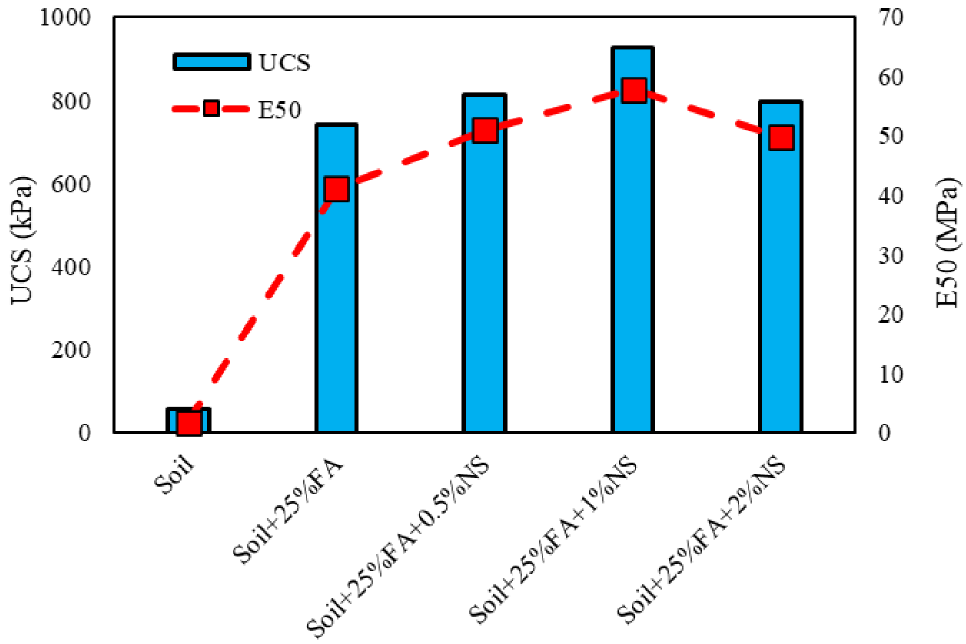

Figure 11. Values of UCS and secant modulus of stabilized samples with fly ash and nanosilica.

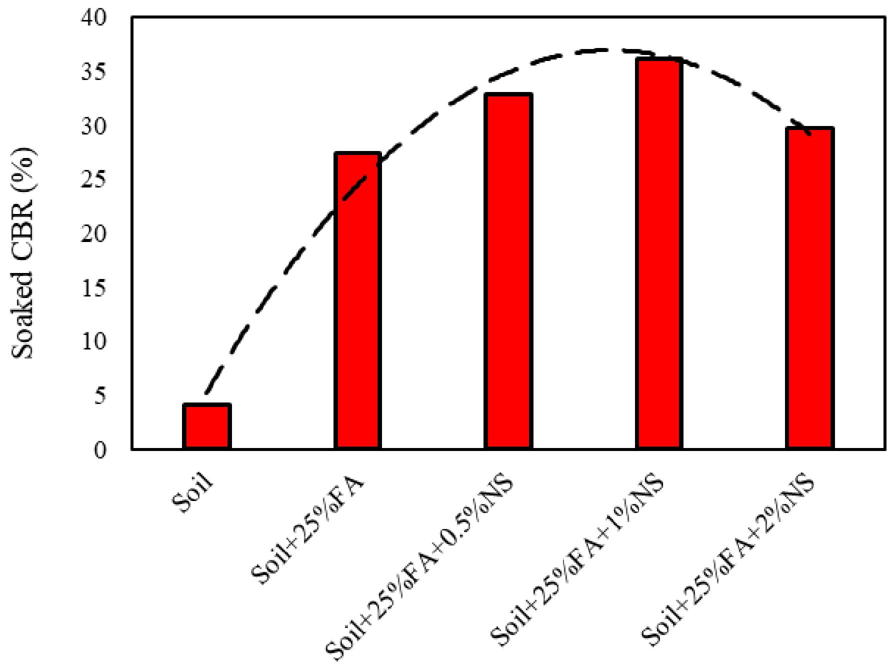

Figure 12. Soaked CBR values of soils stabilized with fly ash and nanosilica.

4. Conclusion

In this study, the effect of nanosilica on soil (obtained from a forest road) stabilized with class C fly ash was investigated by conducting tests on Atterberg limits, standard compaction, unconfined compressive strength, and California bearing ratio. Class C fly ash was used in amounts ranging from 10% to 30%, and nanosilica was added in amounts from 0.5% to 2% relative to the dry weight of the soil as chemical additives. The following conclusions were drawn from the results of the tests:

- Adding up to 25% class C fly ash to soil reduces its liquid limit, plastic limit, and plasticity index. Combining fly ash with soil leads to an increase in the optimum moisture content and a decrease in the maximum dry density. With 30% fly ash, the maximum dry density decreased from 14 to 12.2 kN/m^3, and the optimum moisture content increased from 25.2% to 27% compared to untreated soil.
- Soil strength parameters increase with the addition of class C fly ash up to 25% and decrease with further additions of fly ash. Therefore, the optimal amount of fly ash for improving soil strength in this study was 25%, which resulted in more than a 13-fold increase in compressive strength and approximately a 7-fold increase in soaked CBR after 28 days of curing. This increase is due to pozzolanic reactions and the formation of cementation products, which lead to the bonding of soil particles and stabilizers, as well as the filling of voids.
- The liquid limit and plasticity index of soil containing 25% fly ash increase with the addition of nanosilica. However, the changes in compaction parameters with the addition of nanosilica are not significant.
- Adding nanosilica up to 1% to the soil-fly ash mixture leads to accelerated hydration and an increase in cementitious products. As a result, the compressive strength and soaked CBR of the soil-fly ash mixture increase by 25% and 32%, respectively. The optimal amount of nanosilica to improve strength parameters was found to be 1% when combined with 25% class C fly ash.
- Class C Fly ash and nanosilica increased the stiffness of the samples, such that the secant modulus of the untreated soil, the sample containing 25% fly ash, and the sample containing 25% fly ash and 1% nano-silica were approximately 2, 41, and 58 MPa, respectively.

The economic benefits and reduction of harmful environmental impacts from using these additives will only be determined by conducting a cost analysis and environmental assessment, which should be considered in future studies. It is also recommended to conduct a sensitivity analysis on the results of various experiments for practical applications.

Author Contributions

Sadegh Ghavami: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization, Validation.

Amin Hallaji: Writing – review & editing, Visualization, Investigation, Validation.

Yashar Sandooghsaz: Writing – review & editing, Visualization, Investigation.

Conflict of Interest

The authors declare no competing interests.

References

Abdila, S.R., Abdullah, M.M.A.B., Ahmad, R., Rahim, S.Z.A., Rychta, M., Wnuk, I., Nabiałek, M., Muskalski, K., Tahir, M.F.M., Syafwandi, Isradi, M., & Gucwa, M. (2021). Evaluation on the Mechanical Properties of Ground Granulated Blast Slag (GGBS) and Fly Ash Stabilized Soil via Geopolymer Process. Materials, 14(11), 2833.

Ahmaruzzaman, M. (2010). A review on the utilization of fly ash. Progress in Energy and Combustion Science, 36(3): 327–363.

Aksu, G., & Eskisar, T. (2023). The geomechanical properties of soils treated with nanosilica particles. Journal of Rock Mechanics and Geotechnical Engineering, 15(4): 954–969.

American Coal Ash Association. (2003). Fly Ash Facts for Highway Engineers; Technical Report No. FHWA-IF-03-019; FHWA: Washington, DC, USA.

Arora, A., Singh, B., & Kaur, P. (2019). Performance of Nano-particles in stabilization of soil: A comprehensive review. Materials Today: Proceedings, 17: 124-130.

Arora, S., & Aydilek, A.H. (2005). Class F fly-ash-amended soils as highway base materials, Journal of Materials in Civil Engineering, 17(6): 640–649.

ASTM C618. (2003). Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. ASTM International, West Conshohocken, PA, USA.

ASTM D1883. (1999). Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils; ASTM International: West Conshohocken, PA, USA.

ASTM D2166. (2013). Standard Test. Method for Unconfined Compressive Strength of Cohesive Soil. ASTM International: West Conshohocken, PA, USA.

ASTM D422. (2007). Standard Test Method for Particle-Size Analysis of Soils. ASTM International: West Conshohocken, PA, USA.

ASTM D4318. (2005). Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International: West Conshohocken, PA, USA.

ASTM D698. (2000). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort. ASTM International: West Conshohocken, PA, USA.

ASTM D854. (2002). Standard Test Method for Specific Gravity of Soil Solids by Water Pycnometer. ASTM International: West Conshohocken, PA, USA.

Bagheri, A., Parhizkar, T., Madani, H. & Raisghasemi, A.M. (2013). The influence of different preparation methods on the aggregation status of pyrogenic nanosilicas used in concrete. Materials and Structures, 46: 135–143.

Bahmani, S. H., Huat, B.B., Asadi, A., & Farzadnia, N. (2014). Stabilization of residual soil using SiO_2 nanoparticles and cement. Construction and Building Materials, 64, 350–359.

Bhavitha, K., Gangavaram, P., Revuru, P.K., & Rohilla, S. (2024). Assessing the Geotechnical Properties of Lime-Stabilized Black Cotton Soil in the Presence of Nanosilica. International Journal of Geomechanics, 24(12), 06024024.

Bin-Shafique, S., Rahman, K., Yaykiran, M., & Azfar, I. (2010). The long-term performance of two fly ash stabilized fine-grained soil subbases. Resources, Conservation and Recycling, 54(10): 666–672.

Camargo, F.F., Edil, T.B., & Benson, C.H. (2013). Strength and stiffness of recycled materials stabilised with fly ash: a laboratory study. Road Materials and Pavement Design, 14(3): 504–517.

Çokça, E. (2001). Use of class C fly ashes for the stabilization of an expansive soil. Journal of Geotechnical and Geoenvironmental Engineering, 127(7): 568–573.

Edil, T.B., Acosta, H.A. & Benson, C.H. (2006). Stabilizing soft fine-grained soils with fly ash. Journal of Materials in Civil Engineering, 18(2): 283–294.

Ghavami, S. (2024). A Comparative Study on the Effect of Cement Kiln Dust, Fly Ash, and Ground Granulated Blast Furnace Slag on Compaction Characteristics and California Bearing Ratio of Clay Soils. Journal of Transportation Infrastructure Engineering, 10(2): 57–70.

Ghavami, S., Farahani, B., Jahanbakhsh, H. and Moghadas Nejad, F. (2018). Effects of Silica Fume and Nano-silica on the Engineering Properties of Kaolinite Clay. AUT Journal of Civil Engineering, 2(2): 135–142.

Ghavami, S., & Rajabi, M. (2021). Investigating the Influence of the Combination of Cement Kiln Dust and Fly Ash on Compaction and Strength Characteristics of High-Plasticity Clays. Journal of Civil Engineering and Materials Application, 5(1), 9–16.

Ghavami, S., Jahanbakhsh, H., Saeedi Azizkandi, A. & Moghadas Nejad, F. (2021a). Influence of sodium chloride on cement kiln dust-treated clayey soil: strength properties, cost analysis, and environmental impact. Environment, Development and Sustainability, 23: 683–702.

Ghavami, S., Naseri, H., Jahanbakhsh, H., & Moghadas Nejad, F. (2021b). The impacts of nano-SiO_2 and silica fume on cement kiln dust treated soil as a sustainable cement-free stabilizer. Construction and Building Materials, 285, 122918.

Givi, A.N., Rashid, S.A., Aziz, F.N.A., & Salleh, M.A.M. (2013). Influence of 15 and 80 nano- SiO_2 particles addition on mechanical and physical properties of ternary blended concrete incorporating rice husk ash, Journal of Experimental Nanoscience, 8(1): 1–18.

Hosseini, P., Booshehrian, A., Delkash, M., Ghavami, S., & Zanjani MMK. (2010). Improvement Interfacial Transition Zone of Green Concrete by utilization of nano-SiO_2 particles. 3rd International Conference on Engineering for Waste and Biomass Valorisation, Beijing, China.

Iliyas, S., Idris, A., Umar, I.H., Lin, H., Muhammad, A., & Xie, L. (2024). Experiment and Analysis of Variance for Stabilizing Fine-Grained Soils with Cement and Sawdust Ash as Liner Materials. Materials, 17(10), 2397.

Iran Highway Asphalt Paving Code Number 234. (2010). Iran Management and Planning Organization, Tehran, Iran.

Iranpour, B., & Haddad, A. (2016). The influence of nanomaterials on collapsible soil treatment. Engineering Geology, 205: 40–53.

Karimiazar, J., Teshnizi, E.S., Mirzababaei, M., Mahdad, M., & Arjmandzadeh, R. (2022). California bearing ratio of a reactive clay treated with nano-additives and cement. Journal of Materials in Civil Engineering, 34(2), 04021431.

Krabbenhøft, K., & Wang, J. (2022). Analytical stress–strain relation for soils. Canadian Geotechnical Journal. 59(4): 614–619.

Munda, J., Padhi, J., & Mohanty, S. (2021). Investigation on performance of expansive soil stabilized with fly ash and nano-SiO_2. Materials Today: Proceedings, 67: 1268–1275.

Nath, B.D., Ali Molla, M.K., & Sarkar, G. (2017). Study on Strength Behavior of Organic Soil Stabilized with Fly Ash. International Scholarly Research Notices, 2017(1), 5786541.

Parsons, R.L., & Kneebone, E. (2005). Field performance of fly ash stabilised subgrades, Proceedings of the Institution of Civil Engineers-Ground Improvement, 9(1): 33–38.

Rajaee, A., Talebi, N., & Abrishami, S. (2025). The impacts of freeze-thaw cycles on polypropylene fiber-reinforced clayey soil stabilized with alkali-activated fly ash. Case Studies in Construction Materials, 22, e04439.

Schaefer, V.R., White, D.J., Ceylan, H., & Stevens, L.J. (2008). Design Guide for improved Quality of Roadway Subgrades and subbases. Iowa Highway Research Board (IHRB Project TR-525).

Seyrek, E. (2018). Engineering behavior of clay soils stabilized with class C and class F fly ashes. Science and Engineering of Composite Materials, 25(2): 273–287.

Shirkhanloo, S., Najafi, M., Kaushal, V., & Rajabi, M. (2021). A Comparative Study on the Effect of Class C and Class F Fly Ashes on Geotechnical Properties of High-Plasticity Clay. CivilEng, 2(4): 1009–1018.

Shojamoghadam, S., Rajaee, A., & Abrishami, S. (2024). Impact of various additives and their combinations on the consolidation characteristics of clayey soil. Scientific Reports, 14(1): 1–25.

Tastan, E.O., Edil, T.B., Benson, C.H., & Aydilek, A.H. (2011). Stabilization of organic soils with fly ash, Journal of Geotechnical and Geoenvironmental Engineering, 137(9): 819–833.

Turan, C., Javadi, A.A., & Vinai, R. (2022). Effects of Class C and Class F Fly Ash on Mechanical and Microstructural Behavior of Clay Soil—A Comparative Study. Materials, 15(5), 1845.

Utsev, T., Tiza, T. M., Mogbo, O., Kumar Singh, S., Chakravarti, A., Shaik, N., & Pal Singh, S. (2021). Application of nanomaterials in civil engineering. Materials Today: Proceedings, 62, 5140-5146.

Wang, L., Liu, Q., Li, X.A., Qin, B., Hong, B., & Shi, J. (2024). Effect of nanosilica on the hydrological properties of loess and the microscopic mechanism. Scientific Reports, 14, 13692.

Yilmaz, Y., Coban, H.S., Cetin, B., & Edil, T.B. (2019). Use of standard and off-spec fly ashes for soil stabilization, Journal of Materials in Civil Engineering, 31(2), 04018390.

Yoobanpot, N., Jamsawang, P., & Horpibulsuk, S. (2017). Strength behavior and microstructural characteristics of soft clay stabilized with cement kiln dust and fly ash residue. Applied Clay Science, 141: 146–156.