CHAPTER-V

GEOTECHNICAL CHARACTERIZATION TEST RESULTS AND DISCUSSION

5.1 INTRODUCTION

The geotechnical characterization of soil aids in understanding and interpreting the behaviour of the soil at a particular site, in addition to determining variables such as moisture content, specific gravity, plasticity, particle size analysis, strength characteristics, and compressibility. The geological formations are complicated in nature. It is often noticed that the properties of the soil at a given site differ considerably both horizontally and with depth. Here, the geotechnical properties of the soil, fly ash, and soil treated with Nano-SiO_2 (NS) and fly ash (FA) has been explained in the following sections. The geotechnical tests performed for this investigation are listed below:

a) Specific gravity determination
b) Grain size distribution analysis
c) Consistency limits determination
d) Standard Proctor compaction test
e) Permeability test
f) Consolidation test
g) Unconfined Compressive Strength (UCS) test
h) Static triaxial (UU) test
i) California Bearing Ratio (CBR) test

5.2 SPECIFIC GRAVITY

The specific gravity of fly ashes varies significantly, from 1.6 to 3.1, whereas most of Indian coal ashes have a specific gravity of roughly 2.0. The specific gravity of coal ash varies depending on a number of characteristics, such as particle size, gradation, and chemical composition (Pandian et al. 1998). The low specific gravity of fly ash could be due to the existence of several hollow cenospheres that prevent entrapped air from being released. The large variation in specific gravity found in fly ashes can be attributed due to the variations in boiler loads, furnace design, and operating circumstances, as well as the degree of coal pulverisation and differential settlement in ash lagoons. Continuously raising the boiler temperature leads to lower specific gravity (Moghal 2017). The specific gravity of fly ash varies between 2.15 and 2.32 when taken from various electrostatic precipitator (ESP) fields of an Indian coal-fired thermal power plant (Shanthakumar et al. 2010). Neyveli fly ash (NFA), Vijayawada fly ash (VFA), and Gulbarga fly ash (GFA) have specific gravities of 2.67, 2.58, and 2.03, respectively (Sivapullaiah et al. 1998). The current study fly ash has a specific gravity of 2.15, which is within the range of Indian fly ash. The specific gravity values of class F fly ash from Power Minerals Ltd. in the UK (Birmingham) and class C fly ash from the MUEG company in Germany (Braunsbedra) were found to be 2.32 and 2.4, respectively (Turan et al. 2022). In India, most fly ash generated is of class F type, which has a larger number of cenospheres than class C fly ash. This is the reason behind the class C fly ash's higher specific gravity in comparison to the class F type (Ram and Mohanty 2022). Fly-ash specific gravities typically range from 2.03-2.49, according to (Martin et al. 1990). The fineness, carbon and iron content, and mineralogy of fly ash all affect its specific gravity (Joshi and Lohtia 1997). Specific gravity is more influenced by the presence of iron and carbon content in the fly ash, as shown by the increasing and decreasing trends that correspond with these two factors (Cabrera and Gray 1973). The soil used in the present investigation has a specific gravity of 2.57. According to Federico et al. 2018 the majority of soils have typical specific gravity values between 2.60 and 2.80. Because fly ash has lower specific gravity values than soils, they have lower dry densities. When fly ash is utilized as a backfill material for retaining walls, the decrease in unit weight is beneficial. Additionally, materials for embankments with lower specific gravities are also preferred (Moghal 2017).

5.3 GRAIN SIZE DISTRIBUTION

The majority of fly ash particles, which are produced when pulverized coal is burned to generate electricity, contain a large number of hollows, light-weight microspheres (Fenelonov et al. 2010; Kolay and Bhusal 2014). About 80-99% of the fly ash particles are able to pass through a 75μ sieve size. Fly ashes are often categorised as fine-grained and lie between the 2 and 75μ silt size range (Martin et al. 1990). Silt-sized fractions as well as some clay-sized fractions are revealed by thorough investigations of the coal ashes produced on the Indian subcontinent (Sridharan et al. 1998). Fly ashes typically exhibit significant levels of reactivity. These particles are spherical, ranging in size from 2 to 25μ, and they have a smooth, glassy surface with good adhesion. Alternatively, certain ashes show moderate reactivity, with most of their spherical particles measuring between 2 and 35μ, which indicates both sintering and surface deposition. Fly ashes react poorly with coarser, irregularly shaped spherical particles (Moghal 2017). Particle size directly influences rheological behaviour and is a major factor in coal slurry settlement. The optimum proportion for the bimodal particle size distribution present in most coal ashes is observed to be 30%, at which the apparent viscosity is determined to be negligible (Singh et al.

2015). The two most crucial characteristics of fly ash for effective use are the size and shape of the particles. The two essential parameters for evaluating fly ash's suitability for use in concrete are its arithmetic mean diameter (AMD) and SPAN (used for particle size distribution). For less SPAN value, the sample can be considered as homogeneous (Sarkar et al. 2005; Sarkar et al.2012). More silt-sized fractions than sand-sized fractions are typically observed in ashes deposited in ponds. Sand-sized fractions and partially silt-sized fractions are present in the bottom ashes, which are rich in coarser particles. Fly ashes from sandy silt to silty sand have coefficient of curvature (C_c) values between 0.73 and 2.16 and coefficient of uniformity (C_u) values between 10 and 13.3. These values indicate that the fly ashes are categorized as poorly graded (Sridharan et al. 1998).

The particle size analysis of present fly ash and soil is illustrated in Fig. 5.1. The fly ash contains a larger amount of sand (76.02%), followed by silt (23.52%) and clay (0.44%). The value of the coefficient of uniformity (C_u) is 7.52, while the coefficient of curvature (C_c) is 4.81. According to the Unified Soil Classification System, fly ash falls into the silty sand (SM) category. The soil has 1.3% sand, 66.67% silt, and 32% clay. According to the Unified Soil Classification System, the soil can be categorised as clay with high plasticity (CH).

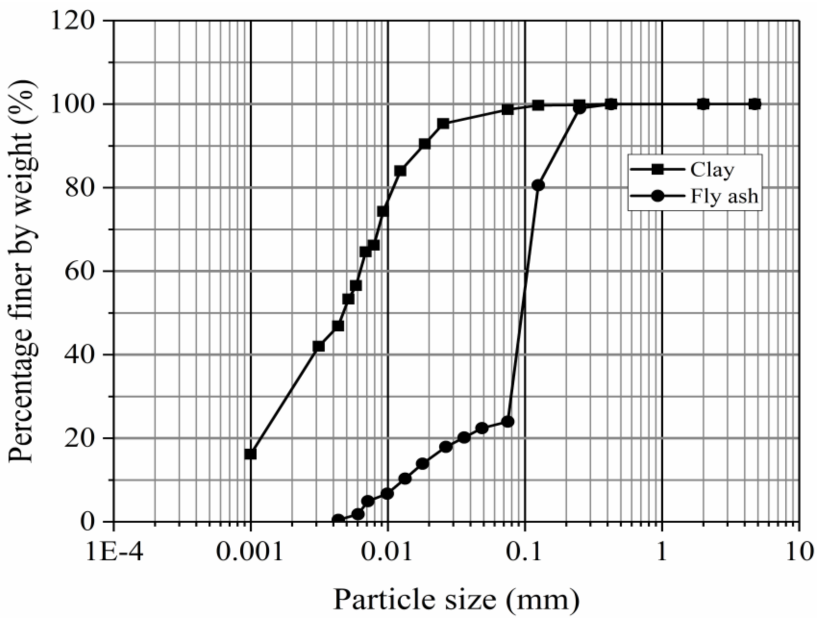
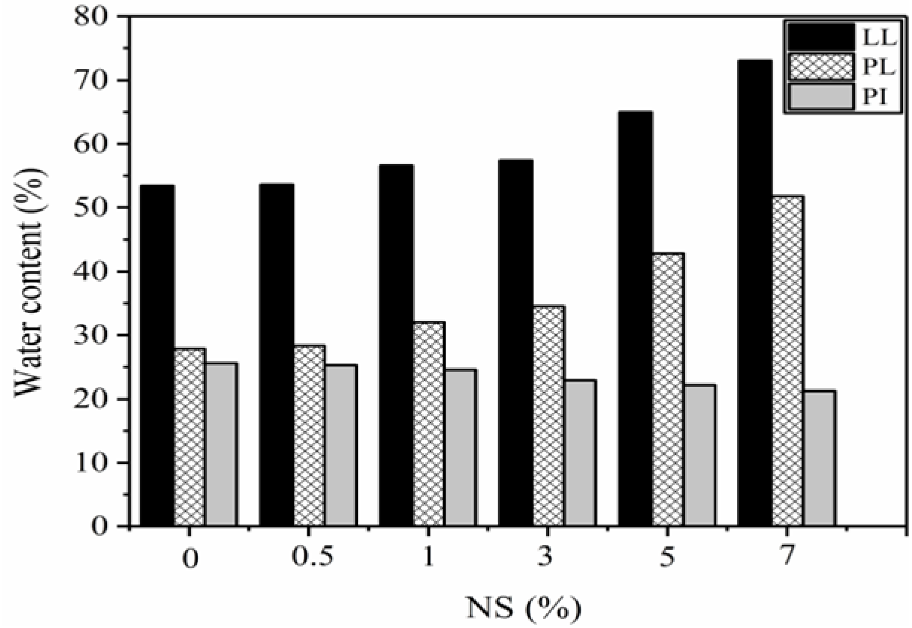


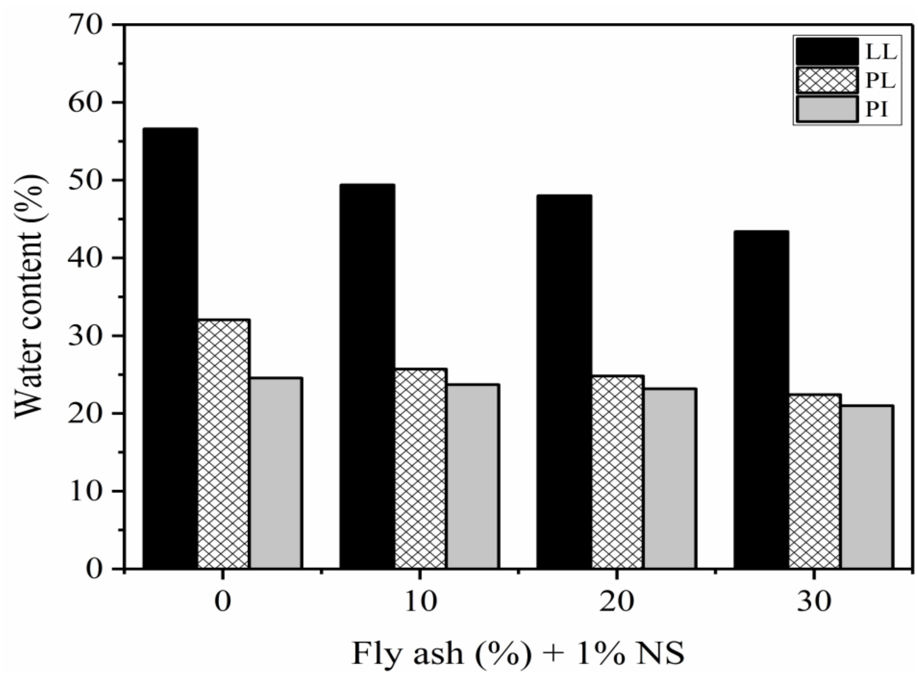
Fig. 5.1. Particle size distribution curve of the considered clayey soil and fly ash.

5.4 CONSISTENCY LIMITS

The behaviour of fine-grained soils, such as clays and silts, under different moisture conditions is described by a set of physical characteristics known as consistency limits. In geotechnical engineering, these characteristics are crucial because they enable engineers to forecast the behaviour of a specific soil under various circumstances, enabling the design of stable and safe structures. The amount of water in the soil affects the firmness or consistency of fine-grained soils. As the water content progressively increases, the soil goes through phases of solid, semi-solid, plastic, and liquid. The water contents at which a consistency changes from one state to another are known as consistency limits. The three boundaries are referred to as the Liquid Limit (LL), Plastic Limit (PL), and Shrinkage Limit (SL). The water content at which the soil exhibits characteristics of a liquid or at which its shear strength is lowest is known as the liquid limit. It is the lowest water content at which the soil remains liquid or the highest water content at which it becomes plastic. The lowest moisture level at which soil can experience plastic deformation is known as the plastic limit. The lowest water content at which a soil sample stops losing volume is known as the shrinkage limit. In other words, when it dries further, it stops contracting. This denotes the maximum water content below which the soil dries without experiencing any volume changes. Plasticity Index (PI) is the difference between the liquid limit and plastic limit. Since fly ash is not plastic, there's less possibility of swelling. There are reports indicating that the liquid limit is between 19-66% and the shrinkage limit is in between 38-65% (Zimar et al. 2022). The plasticity index (PI), which is a reliable measure of compressibility, is correlated with the amount of clay in the soil. A greater PI indicates more compressibility of the soil (Tanzadeh et al. 2019). Here, the consistency limit tests were conducted on the parent soils, Nano-SiO_2 treated soils, and Nano-SiO_2 in combination with fly ash treated soils. Fig. 5.2 (a) represents the effect of Nano-SiO_2 on the consistency limits of the soil composition. The liquid limit (LL) and plastic limit (PL) of the parent soil raised with the rise in the Nano-SiO_2 content. The reason is owing to the greater specific surface area (SSA), chemical component content, and high surface to volume ratio; Nano-SiO_2 can react very actively with the water molecules. Thus, the water absorption capacity of the soil increased, and subsequently, its liquid limit increased (Kalhor et al. 2019; Aksu et al. 2022). The impacts of different fly ash concentrations with the optimum doses of Nano-SiO_2 on the LL, PL, and PI of the clayey soil are illustrated in Fig. 5.2 (b). The LL and PL of the parent clay soil decreased from 53.4%→43.4% and 27.84%→22.4%, respectively, upon the inclusion of 1% of Nano-SiO_2 and 10-30% of fly ash. The inclusion of fly ash to the treated soil decreased the LL and marginally decreased the PL of the treated soil. Due to the coarser particle size of fly ashes compared to the parent soil, the decline in the liquid limit is expected. Additionally, even their finer fractions have no impact on the LL values due to the inert nature of the fly ash (Mir and Sridharan 2013). The C-S-H and C-A-S-H cementitious gel, which is the evolution of cementitious or pozzolanic processes, might reduce the LL and PI values by promoting the aggregation of soil particles (Tastan et al. 2011). Fig. 5.3 depicts the shrinkage limits (SL) of soil treated with Nano-SiO_2 (NS) and 1% Nano-SiO_2 with different variation of fly ash. It is evident from Fig. 5.3(a) that the SL increased as the amount of Nano-SiO_2 increased. Furthermore, as illustrated in Fig. 5.3(b), SL was found to marginally increase upon the combination of the fly ash and the optimised Nano-SiO_2 treated soil.

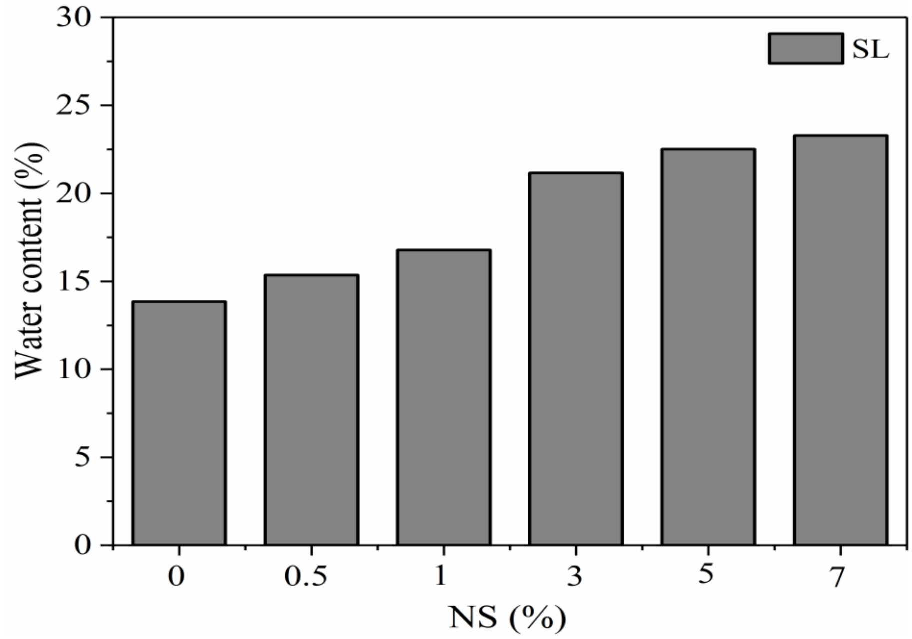


(a)

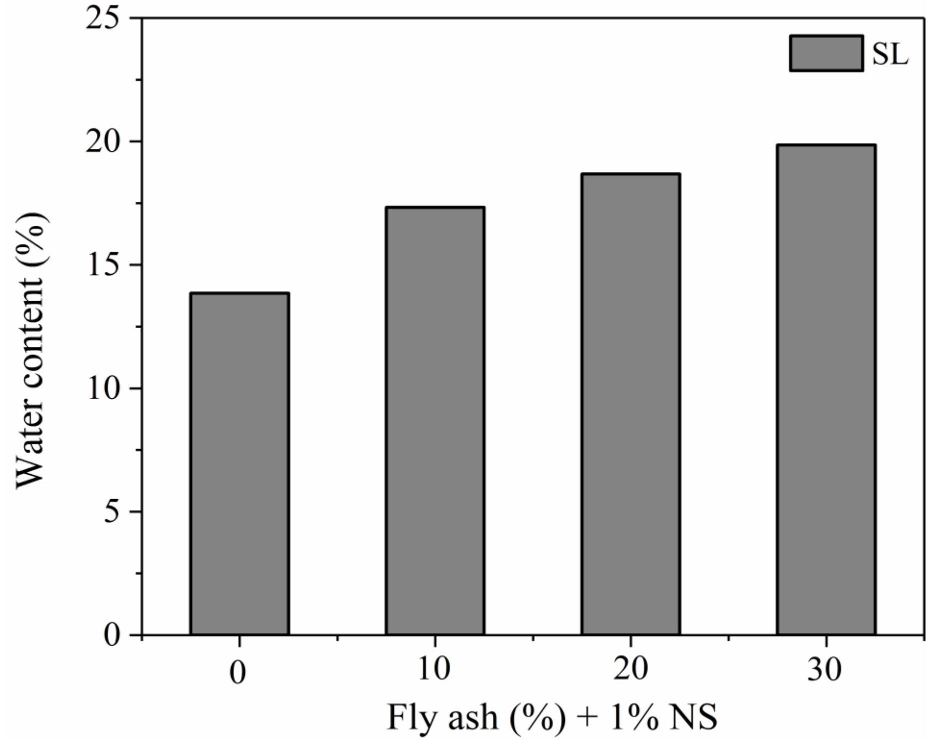


(b)

Fig. 5.2. Consistency limits of clayey soil treated with (a) Nano-SiO_2 (NS) and (b) fly ash + 1% Nano-SiO_2 (NS).



(a)



(b)

Fig. 5.3. Shrinkage limits of clayey soil treated with (a) Nano-SiO_2 (NS) and (b) fly ash + 1% Nano-SiO_2 (NS).

5.5 COMPACTION BEHAVIOUR

Compaction is the process of applying mechanical energy to densify slightly moist soil. The process of compaction involves removing air from a soil mass and rearranging the moist soil particles. This results in a densely packed, compacted soil mass (B M Das 2006). High degrees of compaction in materials lead to increase the shear strength as well as lower the permeability and compressibility (Drnevich et al. 2007). Compaction of the filling material in accordance with earthworks specifications is necessary for road embankments, railway subgrades, canals, earth-dams, and compacted clay liners for waste disposal in order to reduce the intergranular voids and achieve a high density for enhancing strength, rigidity, and decreasing permeability (Parsons 1992; Shimobe and Spagnoli 2020). The impact of the Nano-SiO_2 on the compaction characteristics of the present clayey soil is depicted in Fig. 5.4 (a). It was noticed that the maximum dry unit weight reduced from 15.4 kN/m^3 to 12.6 kN/m^3 with the rise in Nano-SiO_2 content from 0.5% to 7% in the treated soil. Therefore, this may be attributed to the rise in an enormous number of silica nanoparticles that tend to occupy the voids present within the soil matrix under the compaction efforts and formed the lighter soil matrix. The rearrangement of the coarser particles by the finer particles tends to lower the maximum dry unit weight of the soil matrix (Kalhor et al. 2022; Kalhor et al. 2019; Kulkarni et al. 2022). Furthermore, it was noticed that the OMC (optimum moisture content) increased as the specimen's Nano-SiO_2 content raised. As the amount of Nano-SiO_2 in the treated soil increased from 0.5% to 7%, the OMC increased from 21.5% to 34%. This may be due to the extra water demand of the silica nanoparticles for the chemical reactions within the soil matrix (Samala and Mir 2020; Kalhor et al. 2022; Kalhor et al. 2019; Kulkarni et al. 2022). Fig. 5.4 (b) depicts the compaction characteristics of the optimized Nano-SiO_2 and fly ash doses of clayey soil. The results indicated that the maximum dry unit weight had decreased, and that the OMC had only marginally increased to 20% fly ash before decreasing. Due to lower specific gravity of the fly ash than that of the soil, the maximum dry unit weight decreased when it was added (Kumar et al.2007; Savaş et al.2018). The rise in OMC is most likely induced by the rise in fines, whose larger surface areas necessitate greater water requirements (Kumar et al. 2007).

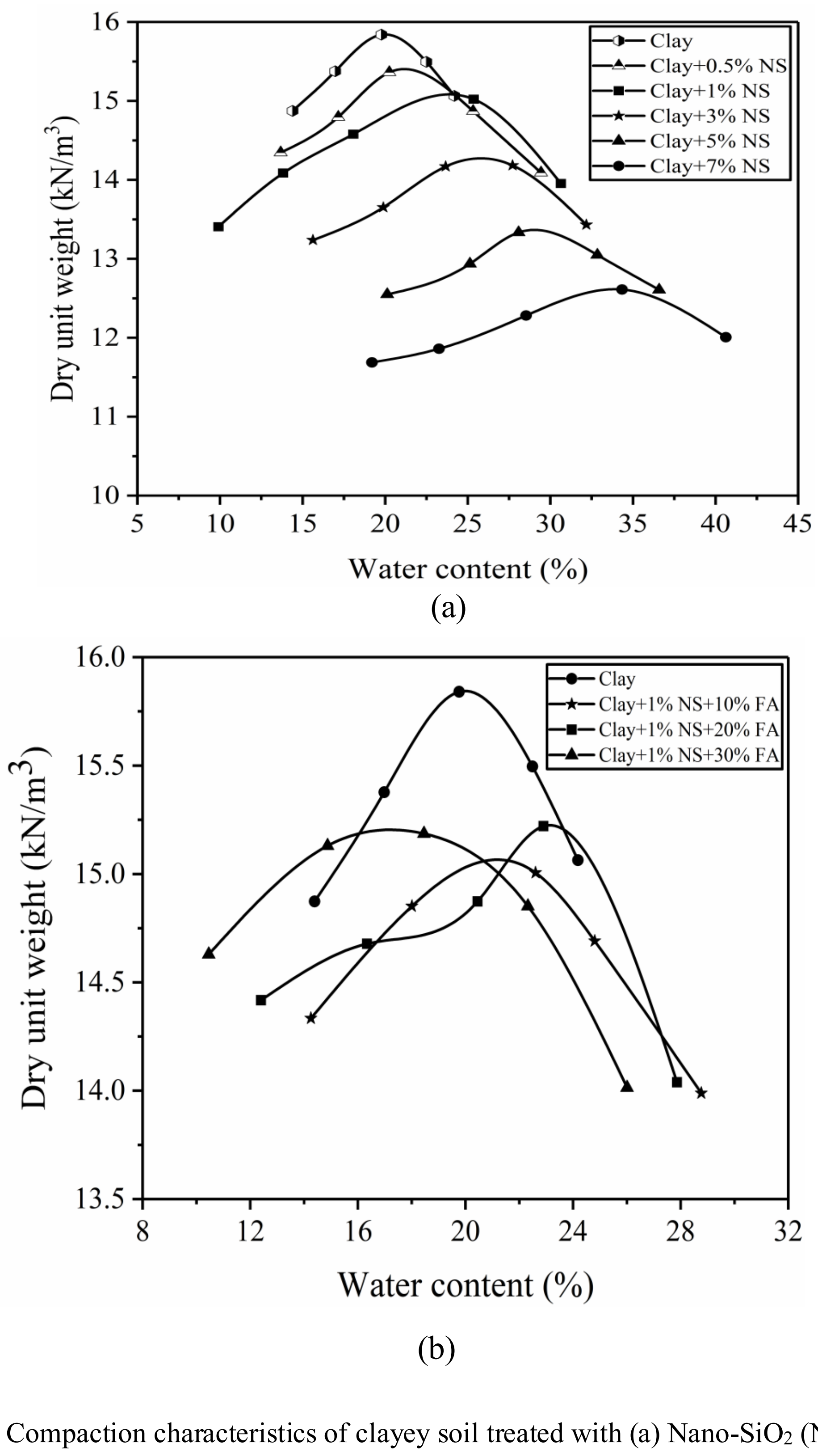


Fig. 5.4. Compaction characteristics of clayey soil treated with (a) Nano-SiO_2 (NS) and (b) fly ash + 1% Nano-SiO_2 (NS).

5.6 PERMEABILITY BEHAVIOUR

The permeability characteristics of the present clayey soil, clayey soil+1% NS, and clayey soil+1% NS+20% FA are found to be 4.92×10^{-6} cm/sec, 4.12×10^{-6} cm/sec, and 3.5×10^{-5} cm/sec respectively. The addition of 1% NS to the clay soil results in a slight reduction in permeability value. The primary reason for the decrease in permeability brought about by the addition of silica nanoparticles is that the nano additions pack the pore spaces between the soil particles. The permeability is decreased and less pores are available for water seepage as a result of nano particles occupying pore spaces (Bahmani et al. 2014). However, the permeability of soil treated with the optimum proportion of fly ash (20%) and nano silica (1%) combination was higher than that of the untreated soil. The presence of fly ash on the high plasticity clay soil, which indicated that the addition of FA altered the interparticle void ratio, increasing permeability; hence, the microscopic features of the soil mixtures might have contributed to the permeability rise. Moreover, the size of silt particles is nearly uniform, which leads to a greater inter-particle void and a more significant inter-particle vacuum (Lekha et al. 2015; Mir and Sridharan 2014). Also, the cation exchange reaction causes flocculation and aggregation, which raise the permeability (Phanikumar 2009).

5.7 CONSOLIDATION BEHAVIOUR

Consolidation is the deformation that develops when there is expulsion of pore water under pressure from the saturated soil causes the volume of the void to decrease and the grains to converge (Holtz et al.1981; Löfman and Korkiala-Tanttu et al. 2021). The compressibility of the soil is one of the most crucial soil characteristics for design considerations. The compressibility properties of soils are ascertained using the oedometer test and are commonly represented by the coefficient of consolidation (c_v)

and the compression index (c_c). The coefficient of consolidation is a rate parameter that is used to estimates the time it will take for a specific amount of compression to occur, whereas the compression index is used to estimate the amount of settlement (Sridharan et al. 2000). Fig. 5.5 displays the void ratio (e) plotted against effective confining pressure (log σ') compression curves for the reconstituted clayey soil, clayey soil + 1% NS, and clayey soil + 1% NS + 20% FA. From Fig. 5.5, it can be shown that the nano silica treated clayey soil has a higher void ratio than the untreated specimen at any stress level during loading and unloading conditions. This is owing to the inclusion of nanomaterial caused a large number of nano-perforations due to its larger specific surface area, which increased the total void ratio. Similar observation was noticed by previous researchers (Thomas et al. 2023; Kannan et al. 2023). Table 5.1 represents the consolidation characteristics of the treated and untreated clayey soil pertain to an effective pressure of 400 kPa to 800 kPa. The compression index values for clayey soil, clayey soil + 1% NS, and clayey soil + 1% NS + 20% FA are found to be 0.26, 0.22 and 0.15, respectively. The co-efficient of volume compressibility values for clayey soil, clayey soil + 1% NS, and clayey soil + 1% NS + 20% FA are found to be 1.41×10^{-4} m^2/kN, 1.12×10^{-4} m^2/kN and 0.77×10^{-4} m^2/kN, respectively. The co-efficient of compressibility values for clayey soil, clayey soil + 1% NS, and clayey soil + 1% NS + 20% FA are observed to be 1.98×10^{-4} m^2/kN, 1.69×10^{-4} m^2/kN and 1.16×10^{-4} m^2/kN, respectively. The addition of fly ash and nano silica to the clayey soil caused a decrease in its plasticity characteristics and the development of pozzolanic activity, which resulted in a decline in the compressibility value. When different pozzolanic materials were used, a similar pattern was also noted by past study (Thomas et al. 2023). The coefficient of consolidation (c_v) was determined using Taylor's square-root-of-time curve-fitting approach. The co-efficient of consolidation values for soil, soil + 1% NS, and soil + 1% NS + 20% FA are found to be 1.57×10^{-7} m^2/sec, 1.33×10^{-7} m^2/sec and 2.26×10^{-7} m^2/sec, respectively. The inclusion of Nano silica resulted in a decrease in the coefficient of consolidation. This is due to the C-S-H gel formation that the Nano silica offers in the soil microstructure, which prevents water passing through the samples (Ghadr et al. 2022). When the optimum amount of fly ash was blended in the composite mixture, resulting in a decrease in the compression index (c_c), coefficient of volume change (m_v), and coefficient of compressibility (a_v). However, the co-efficient of consolidation (c_v) increased. Because the silty nature of fly ash particles increases soil permeability and promote faster drainage that is responsible for the rising c_v by reducing the time required for 90% consolidation (Rangaswamy 2016).

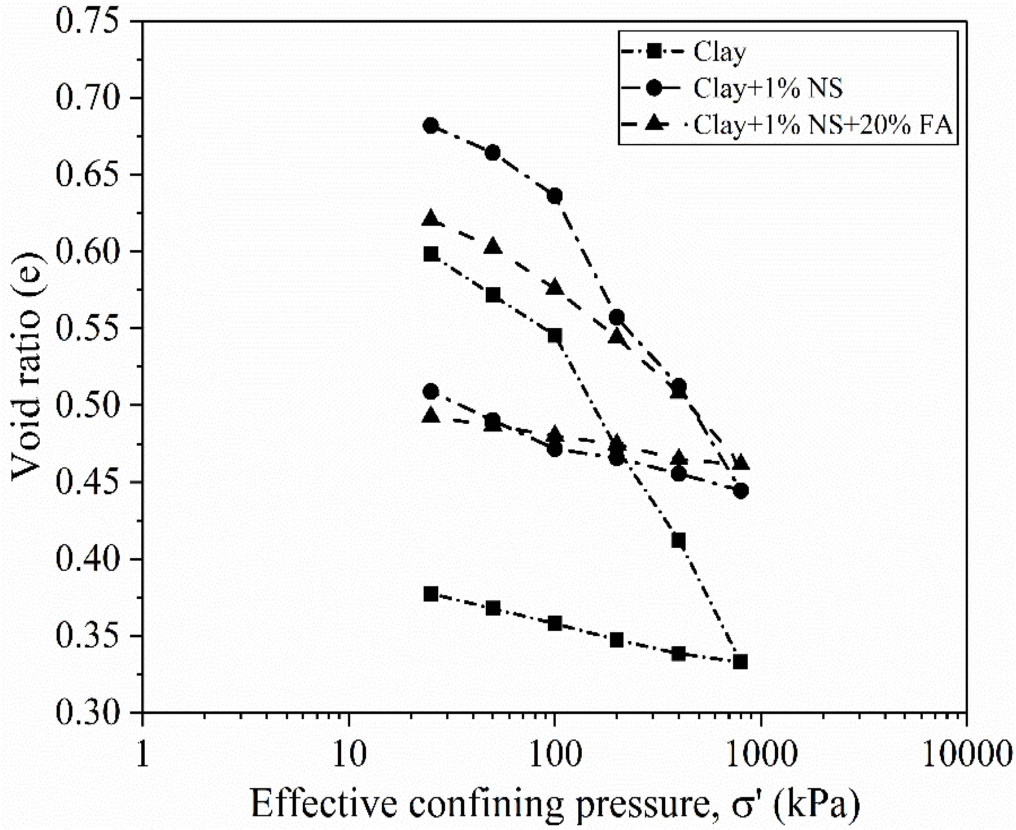


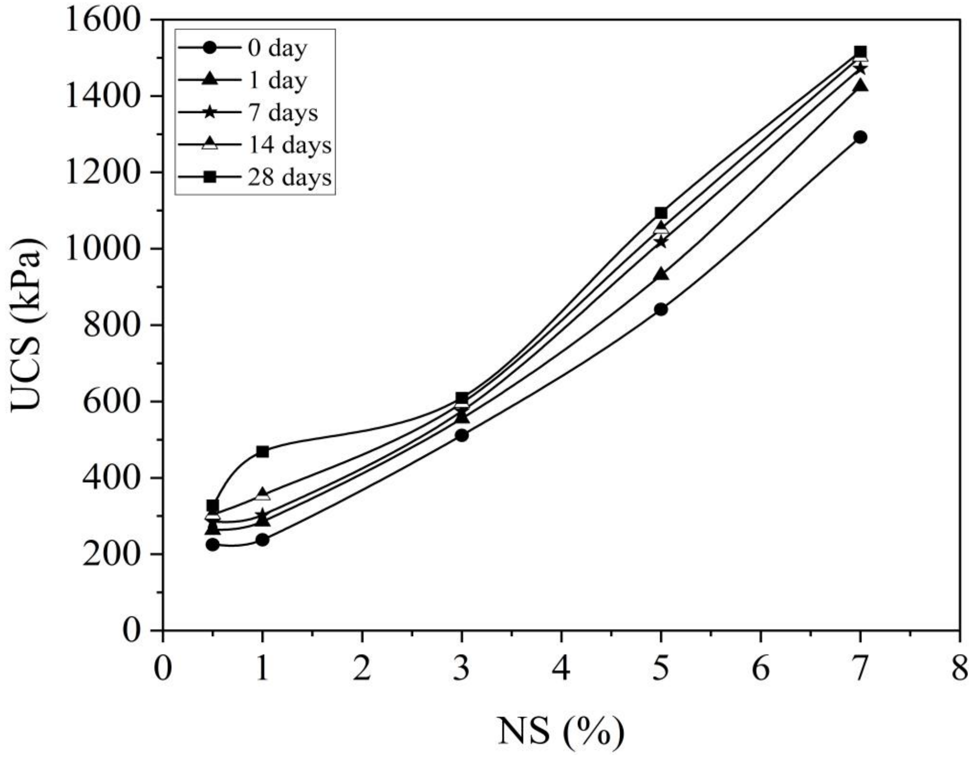
Fig. 5.5. Void ratio versus effective confining pressure of clayey soil, clayey soil+1% NS, and clayey soil+1% NS+20% FA.

Table 5.1. Consolidation characteristics of the treated and untreated clayey soil.

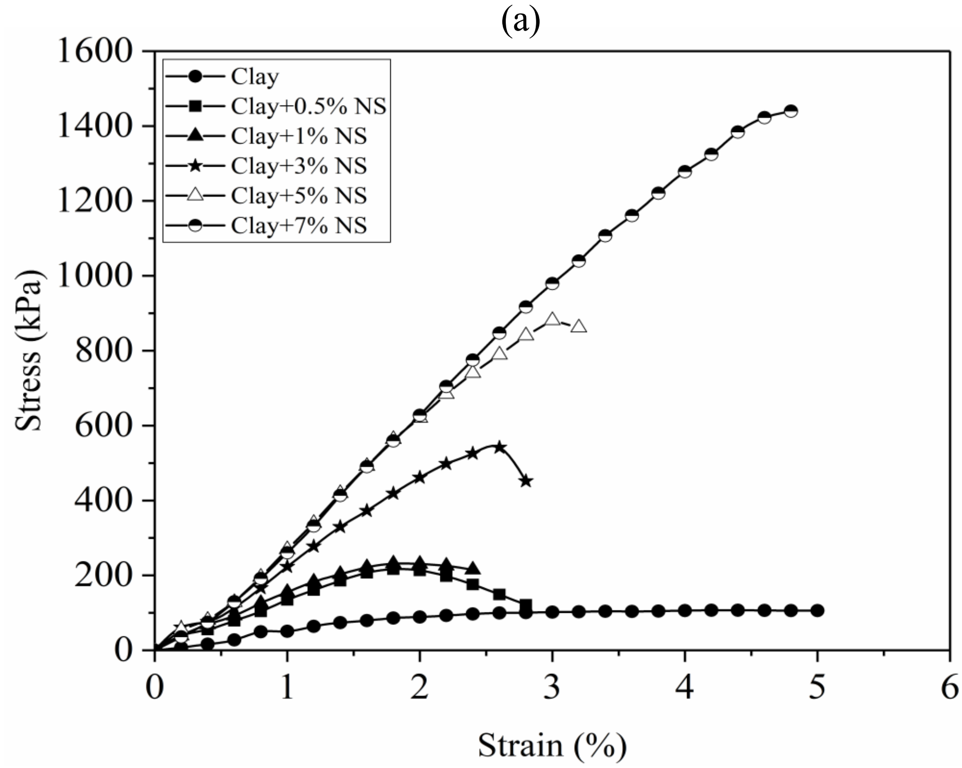
Sample	Compression index, c_c	Co-efficient of volume compressibility, m_v (m^2/kN)	Co-efficient of compressibility, a_v (m^2/kN)	Co-efficient of consolidation, c_v (m^2/sec)
Clayey soil	0.26	1.41×10^{-4}	1.98×10^{-4}	1.57×10^{-7}
Clayey soil+1% NS	0.22	1.12×10^{-4}	1.69×10^{-4}	1.33×10^{-7}
Clayey soil+1% NS +20% FA	0.15	0.77×10^{-4}	1.16×10^{-4}	2.26×10^{-7}

5.8 UNCONFINED COMPRESSIVE STRENGTH (UCS)

The impact of Nano-SiO_2 on the UCS of samples under the curing ages of 0, 1, 7, 14, and 28 days are illustrated in Fig. 5.6 (a). Fig. 5.6 (b) depicts the typical stress-strain curves of the soil matrix treated with Nano-SiO_2. It was noticed that the shapes of the stress-strain response varied substantially as the amount of Nano-SiO_2 content raised from 0.5% to 7%, and the UCS of the soil matrix enhanced tremendously with the curing age. The strength of the specimens achieved at 28 days was more than that of the 1, 7, and 14 days of curing. Fig. 5.7 demonstrates the strength growth rate of the soil treated with Nano-SiO_2 at various aging stages. With the inclusion of 0.5%, 1%, 3%, 5%, and 7% of Nano-SiO_2, the UCS values during the 28-days curing period enhanced by 45.68%, 97.12%, 19.24%, 29.98%, and 17.34%, respectively, in comparison to the first day curing of the treated soil matrix. Although the highest compressive strength was attained with the higher loads of Nano-SiO_2, the strength growth rate was marginally lower than the lower loads of Nano-SiO_2. A significant development in strength was achieved with 1% of Nano-SiO_2. Also, it was challenging to prepare samples with higher loads of Nano-SiO_2. A similar observation was also reported by past researchers (Thomas and Rangaswamy 2020). The increase in the strength is the result of the C-S-H gel filling many of the spaces in the soil matrix (Kulkarni and Mandal 2022).



(a)



(b)

Fig. 5.6. (a) UCS curve and (b) Stress-strain curve for soil treated with Nano-SiO_2 (NS).

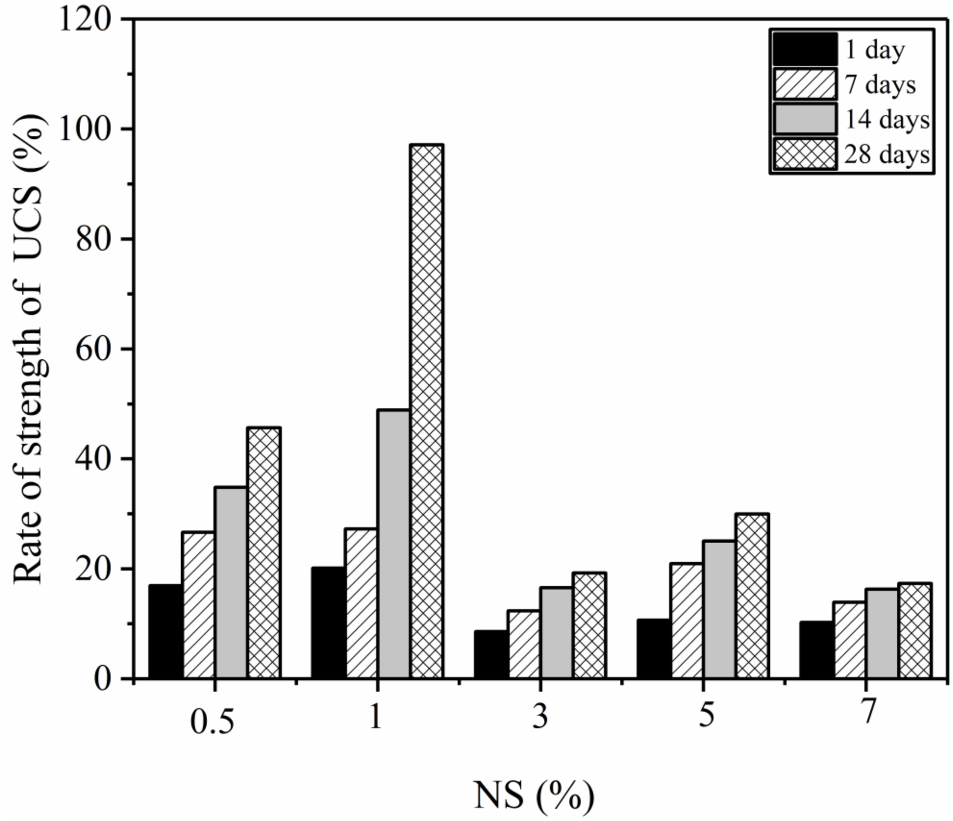


Fig. 5.7. Rate of strength improvement in UCS value for soil treated with Nano-SiO_2 (NS).

5.8.1 Comparison of Strength Characteristics of the Untreated and Treated Soil

For the last two decades, many researchers have documented the utilization of nanomaterials for the strength improvement of weak soils. Among various nanomaterials, Nano-SiO_2 is considered as most widely and effectively used stabilizer. Fig. 5.8 illustrates the comparison among various types of soil with Nano-SiO_2 and different types of additives used in the past and the present study. The UCS value of clay with low plasticity (CL) soil increased to about 197.9% with 2% Nano-SiO_2 at 28 days of curing (Kalhor et al. 2019). Furthermore, the UCS value of CL soil increased to about 427.16% at 28 days of curing age (Samala and Mir 2020). The compressive strength was increased by 508.8% with the inclusion of 1% Nano-SiO_2 for high plastic CH soil (Thomas and Rangaswamy 2020). The combination of 7% nanoparticles with 0.7% fibre enhanced the UCS value of CH soil to about 275.65% (Tomar et al. 2020). The compressive strength of 3% gas oil-contaminated clay increased by 210.9% with the inclusion of 3% Nano-SiO_2 and 3% hydrated lime (Nezhad et al.2021). In the current study, the UCS value was increased to about 405.27% with the inclusion of 1% Nano-SiO_2 in CH soil. After analysing the findings of the current study to that of the past studies, it can be deduced that adding a very small amount of Nano-SiO_2 along with fly ash can substantially improve the strength characteristics of the soil and the composite mix, which can be widely used for a variety of geotechnical engineering purposes.

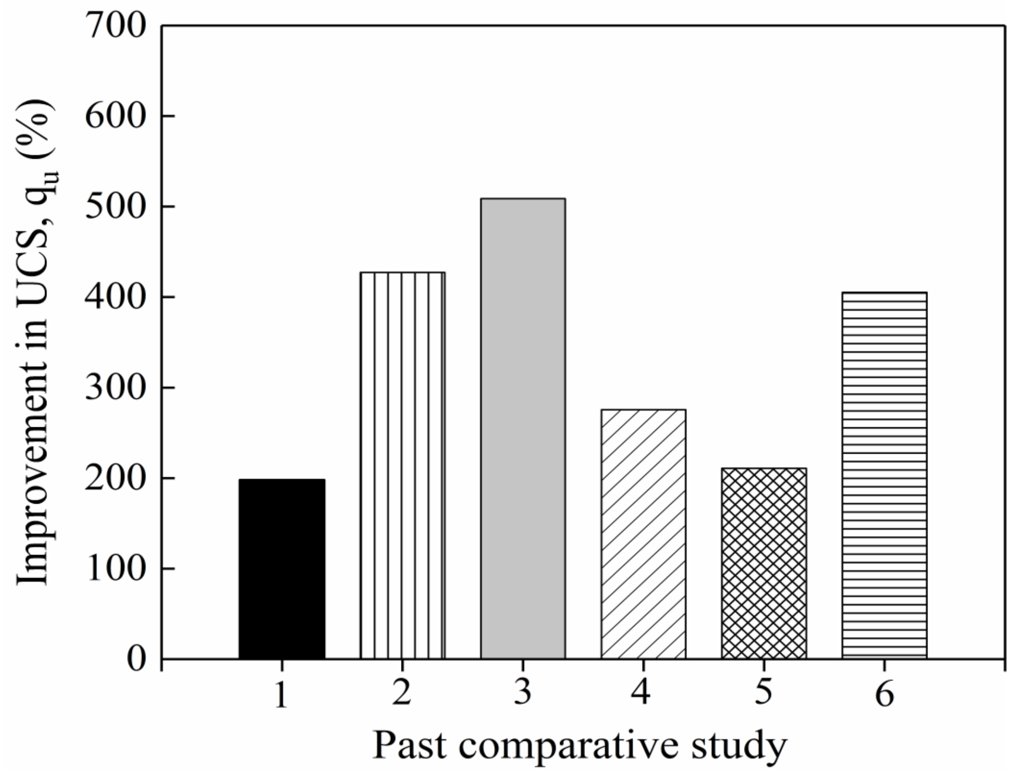
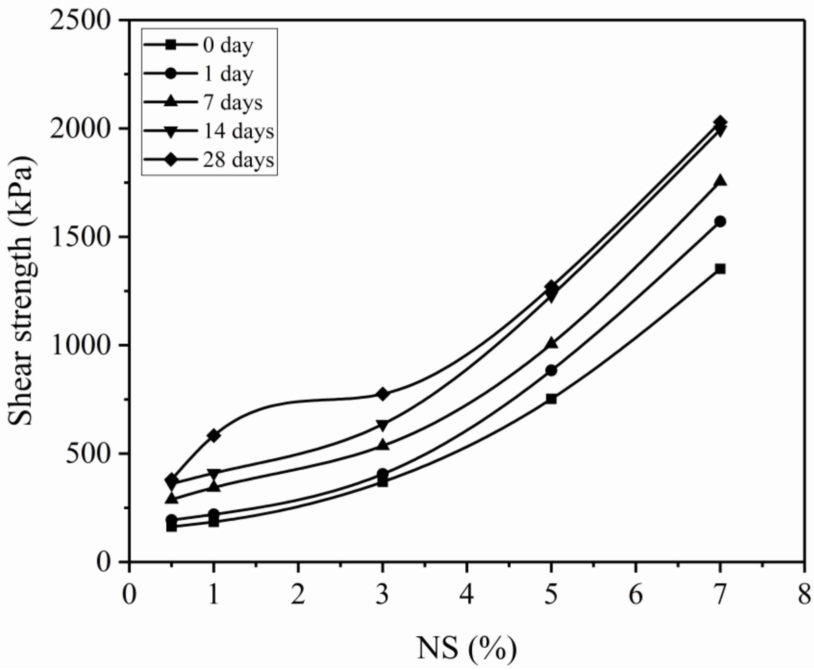


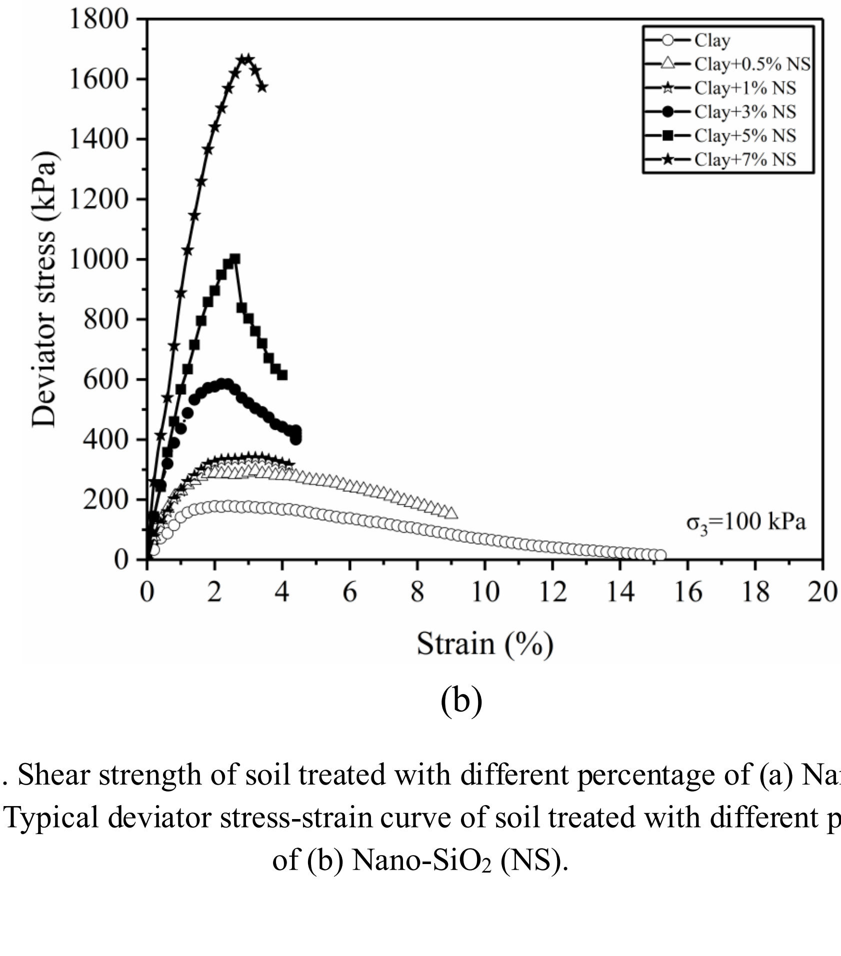
Fig. 5.8. Comparisons of strength improvement of soil with Nano-SiO_2 and other additives at 28 days curing. (1. Kalhor et al.2019, 2. Samala and Mir 2020, 3. Thomas and Rangaswamy 2020,4. Tomar et al.2020, 5. Nezhad et al.2921, 6. Present study).

5.9 SHEAR STRENGTH PARAMETERS

The shear strength variation of soil treated with Nano-SiO_2 (NS) and fly ash + 1% Nano-SiO_2 (NS) is shown in Fig. 5.9 (a) and Fig. 5.10 (c) respectively. Fig. 5.9 (a) depicts that the addition of 0.5%, 1%, 3%, 5%, and 7% of Nano-SiO_2 at the 28-days curing period increased the shear strength of the specimen by 133.38%, 215.04%, 109.59%, 100.59%, and 50.06% in comparison to the first day curing of the stabilized soil matrix. The typical deviator stress-strain curves of the triaxial (UU) test performed on the clayey soil treated with 0.5%, 1%, 3%, 5%, and 7% of Nano-SiO_2 under a confining pressure of 100 kPa are displayed in Fig. 5.9 (b). It was noticed that for treated specimens, the stress-strain curves exhibit a rapid growth phase and have a tendency to sharply increase the deviator stress as the amount of Nano-SiO_2 content increases. The evolution of the cementitious calcium silicate hydrate (C-S-H) gel and the development of pozzolanic activity with curing days are the two factors that can be attributed to the increase in shear strength of the specimens (Kalhor et al.2022; Choobbasti et al.2018). This is due to the extraordinarily aggressive reactions between the Ca $(OH)_2$ and Nano-SiO_2 in the soil matrix. The variation in the shear strength parameters (c & ϕ) of the soil matrix is summarized in Table 5.2. With the addition of different percentages (0.5, 1, 3, 5 and 7) % of nano silica to the clay soil, the shear strength parameters, cohesion increased from 77.14 kPa to 420.49 kPa and the angle of shearing resistance increased from 16.68° to 29.61° for 0 day. Furthermore, with the addition of optimum content of nano silica (1% NS) and different variation of fly ash (10, 20 and 30) % to the clay soil, there was a slight increase of cohesion from 103.48 kPa to 103.76 kPa and then it deceased to 99.66 kPa and there was a slight increase in angle of shearing resistance from 18.61° to 19.34° and then it decreased to 19.28° for 0 day. The results revealed that shear strength parameters of the treated soil raised with the rise in Nano-SiO_2 and fly ash dosages. In comparison to the results of the UCS test, the triaxial test results are more pertinent. The shear strength was enhanced to approximately 232%, 295%, and 214% at 28 days of curing with the addition of 1% Nano-SiO_2 and different fly ash contents (10%, 20%, and 30%), respectively. The highest shear strength was obtained with 1% Nano-SiO_2 and 20% fly ash, as displayed in Fig. 5.10 (c). The typical deviator stress-axial strain curves of 1% Nano-SiO_2 and various fly ash contents (10%, 20%, and 30%) at a confining pressure of 100 kPa are depicted in Fig. 5.10 (d). Furthermore, the cementitious and pozzolanic reactions with the presence of siliceous or aluminous materials in the soil matrix or binding agent result in the development of calcium silicate hydrate (C-S-H) and calcium aluminate silicate hydrate (C-A-S-H) gel, which results in the strength growth rate of the specimens induced by the addition of fly ash (Tastan et al. 2011). The strength development of the stabilized soils is greatly influenced by the stabilizer components, particularly calcium oxide (CaO). The strength of the lime treated soil is affected by the CaO content at all curing times. Early strength improvements for cement, fly ash, and fly ash-cement mixtures are driven mainly by the CaO concentration, while SiO_2 and Al_2O_3 significantly influence after longer curing durations (Mahedi 2020).

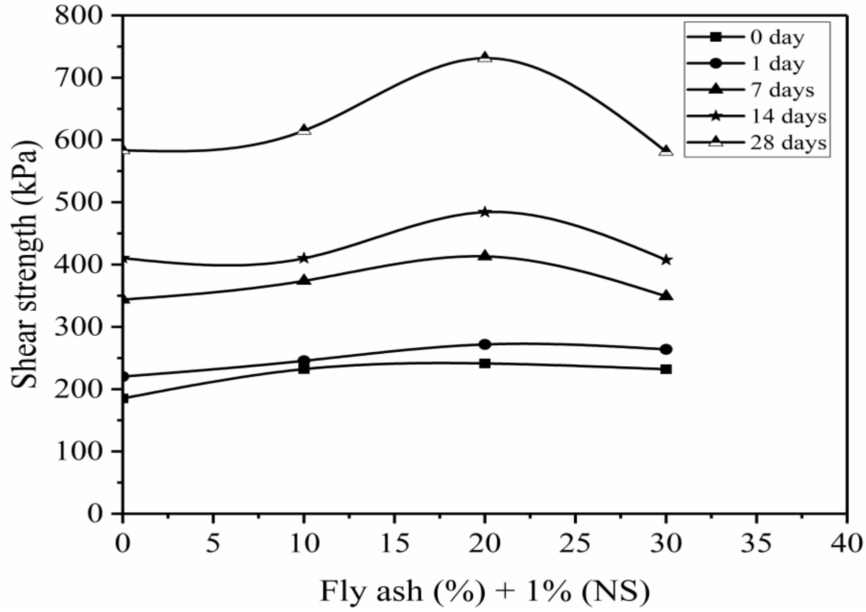


(a)

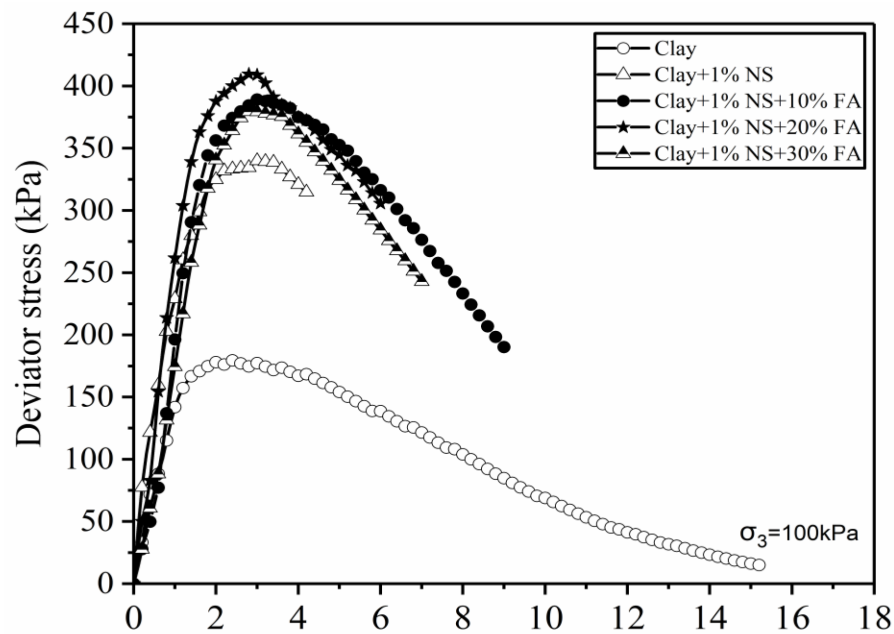


(b)

Fig. 5.9. Shear strength of soil treated with different percentage of (a) Nano-SiO_2 (NS) and Typical deviator stress-strain curve of soil treated with different percentage of (b) Nano-SiO_2 (NS).



(c)



(d)

Fig. 5.10. Shear strength of soil treated with (c) fly ash + 1% Nano-SiO_2 (NS); and Typical deviator stress-strain curve of soil treated with (d) fly ash + 1% Nano-SiO_2 (NS).

Table 5.2. Summary of shear strength parameters obtained from triaxial (UU) tests.

Category	0 day		1 day		7 days		14 days		28 days	
	c (kPa)	ϕ (°)	c (kPa)	ϕ (°)	c (kPa)	ϕ (°)	c (kPa)	ϕ (°)	c (kPa)	ϕ (°)
Clay	35.68	15.43	-	-	-	-	-	-	-	-
Clay+0.5%NS	77.14	16.68	93.10	16.86	125.12	19.70	141.37	22.09	145.73	22.65
Clay+1%NS	83.67	17.76	101.27	17.95	138.51	21.48	144.43	24.34	214.55	24.53
Clay+3% NS	152.54	21.23	152.79	23.15	183.05	25.67	208.06	26.88	239.27	28.50
Clay+5%NS	270.91	21.60	296.35	23.4	347.75	26.88	364.49	30.34	367.66	30.88
Clay+7%NS	420.49	29.61	425.26	32.63	425.59	34.97	425.76	37.53	427.04	37.82
Clay+1%NS+ 10%FA	103.48	18.61	108.06	18.97	140.79	22.9	158.26	22.71	201.23	26.82
Clay+1%NS+ 20%FA	103.76	19.34	111.45	20.49	133.64	25.73	140.59	28.04	182.87	31.88
Clay+1%NS+ 30%FA	99.66	19.28	108.86	20.31	153.03	19.46	170.71	21.17	145.00	31.01

5.9.1 Failure Behaviour of the Untreated and Treated Soil

The typical mode of failure patterns of the specimens after static triaxial (UU) tests for the untreated soil, soil treated with Nano-SiO_2, and soil treated with optimized Nano-SiO_2 and fly ash are depicted in Fig. 5.11. As depicted, bulging failure occurs in pure clay Fig. 5.10 (b). The specimens with 1% of Nano-SiO_2 tend to behave as a bulging failure with slight development of crack and beyond 3% of Nano-SiO_2, resulting in a brittle failure of the specimens. The specimens stabilized with optimized Nano-SiO_2, and fly ash experienced shear failure mode, approximately making an angle of ($45°+\frac{\Phi}{2}$). An identical failure surface was noticed by past researchers (Dai et al. 2020) for the expansive soil. Further, another researcher (Wang et al. 2019) discussed the failure modes of the untreated and fibre-reinforced soil treated with lime. In comparison to lime-stabilized soil, the bridging effect of fibres in the fibre-reinforced soil was found to control the formation of the shear failure band and hence impose higher ductile stress-strain behaviour.

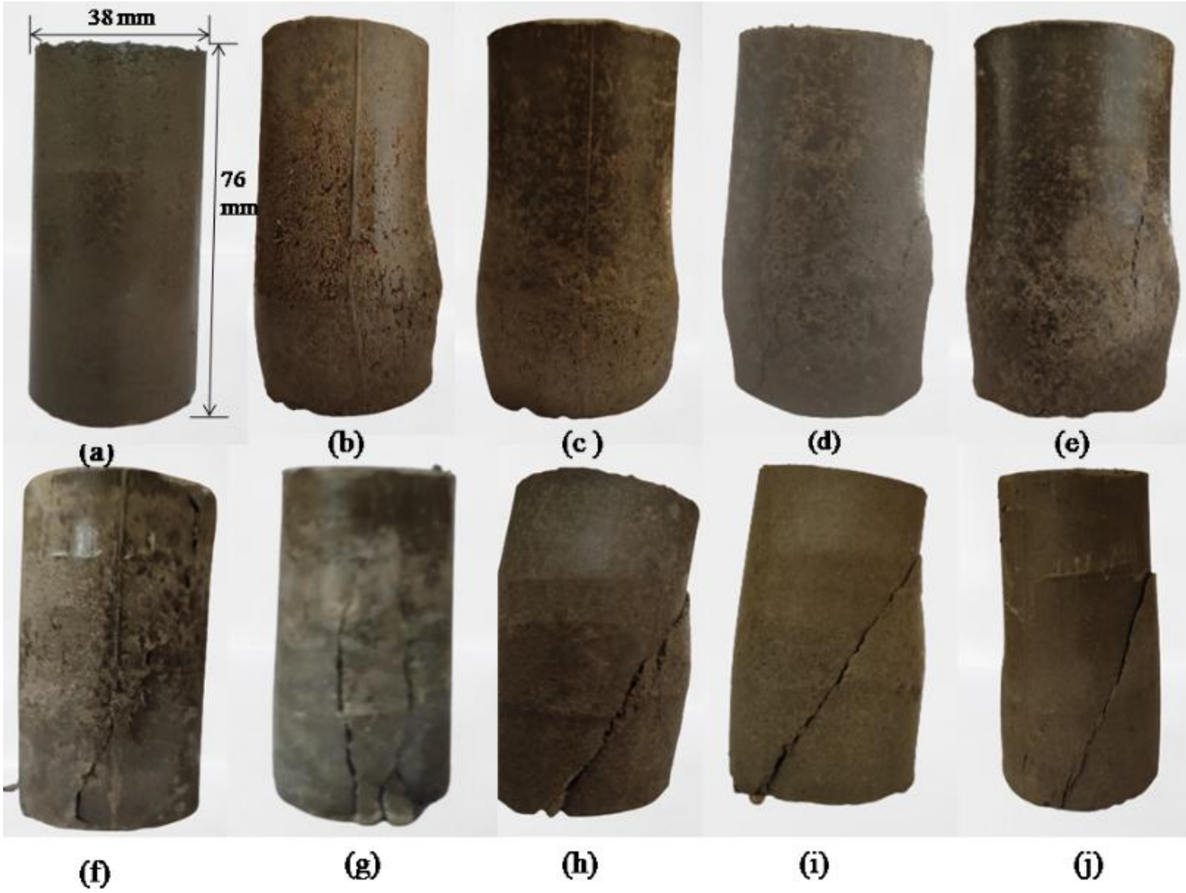
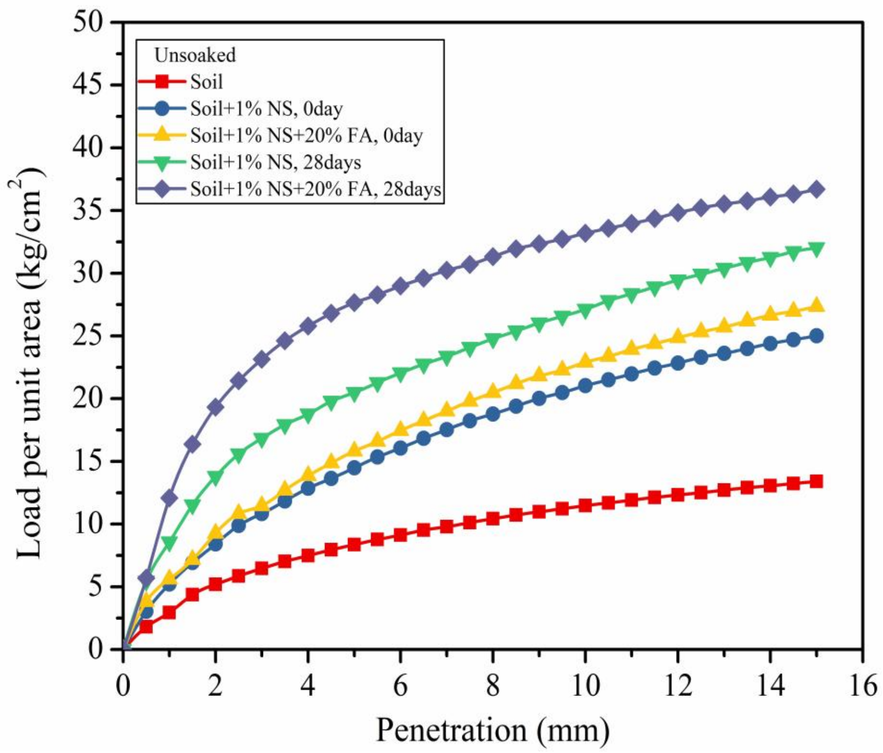


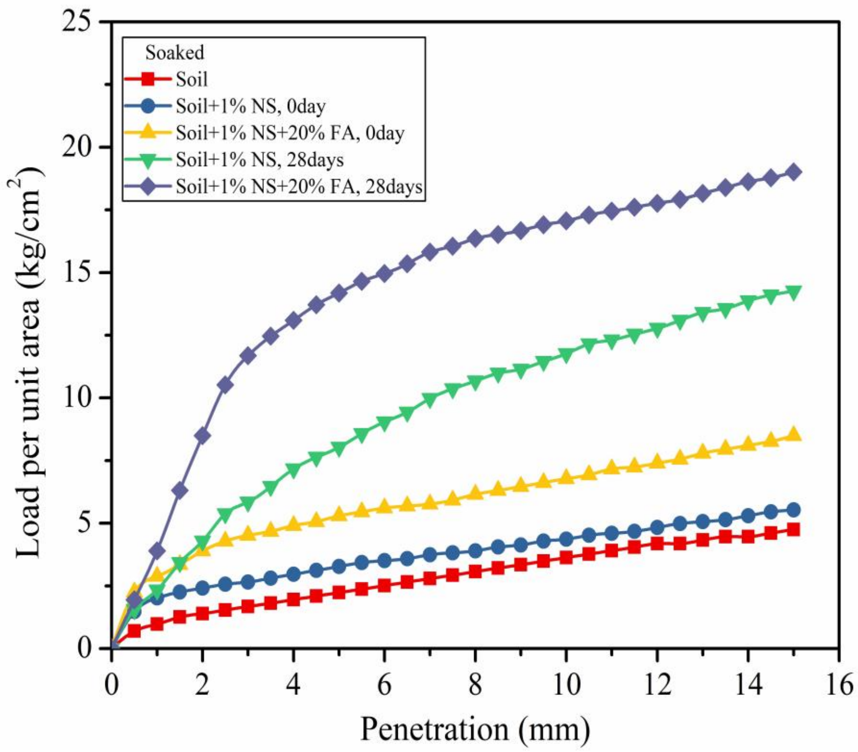
Fig. 5.11. Typical modes of failure surfaces from Triaxial (UU) Test at σ_3=100kPa (a) Typical sample (b) Soil (c) Soil+0.5% NS (d) Soil+1%NS (e) Soil+3% NS (f) Soil+5% NS (g) Soil+7% NS (h) Soil+1%NS+10%FA (i) Soil+1%NS+20%FA (j) Soil+1%NS+30%FA.

5.10 CALIFORNIA BEARING RATIO (CBR)

The bearing capacity of the subgrade, which is significantly impacted by fluctuations of moisture in the subgrade, is one crucial parameter in the design of flexible pavements. The most widely used technique for determining the subgrade bearing capacity is the California Bearing Ratio (CBR). The load needed to accomplish a specific penetration on a given subgrade is compared to the load required to achieve the same penetration on standard material (Wimalasena and Gallage 2022). The CBR value indirectly assesses the thickness of the subgrade materials that are used in the construction of highway, airport, and railroad pavement (Taskiran 2010). The strength of the subgrade soil and the traffic volume are necessary for the pavement design. The subgrade soil characteristics may not be adequate most of the time. These soils are regarded as poor since they are not immediately appropriate for pavement construction (Praveen et al. 2021). The weak subgrade soil, which often has a Soaked California Bearing Ratio (CBR) value of less than 3%, must be stabilized in order to construct pavement (Trzebiatowski et al. 2004). Fig. 5.12 depict the load-penetration graph of soil, soil+1% NS, and soil+1% NS+20% FA under both unsoaked and soaked condition for 0 day and 28 days curing period. The unsoaked CBR value of the present investigation of soil, soil+1% NS, and soil+1% NS+20% FA are 8.37, 14.13, and 15.47, while the soaked CBR value of soil, soil+1% NS, and soil+1% NS+20% FA are 2.19, 3.67 and 6.12 (Fig. 5.13). The unsoaked CBR values of the present investigation of soil+1% NS and soil+1% NS+20% FA are 22.26 and 30.61, while soaked CBR values of soil+1% NS and soil+1% NS+20% FA are 7.68 and 15.02 under 28 days of curing days. Because of the very poor subgrade strength (CBR=2) and poor subgrade strength (CBR= 3 to 4), it is not appropriate for pavement. For high plastic clays and silts, the soaked CBR value typically ranges from 2 to 3. The requirement is that all rural roads have a minimum sub-grade soaked CBR of 5% (IRC: SP:72-2015). The present combination of 1% NS + 20% FA can give significant strength to high plastic clay soil, and it can be recommended for usage as the subgrade for rural roads.



(a)



(b)

Fig. 5.12. Load-penetration curve of soil, soil+1% NS, and soil+1% NS+20% FA under both (a) unsoaked and (b) soaked condition for 0 day and 28 days curing period.

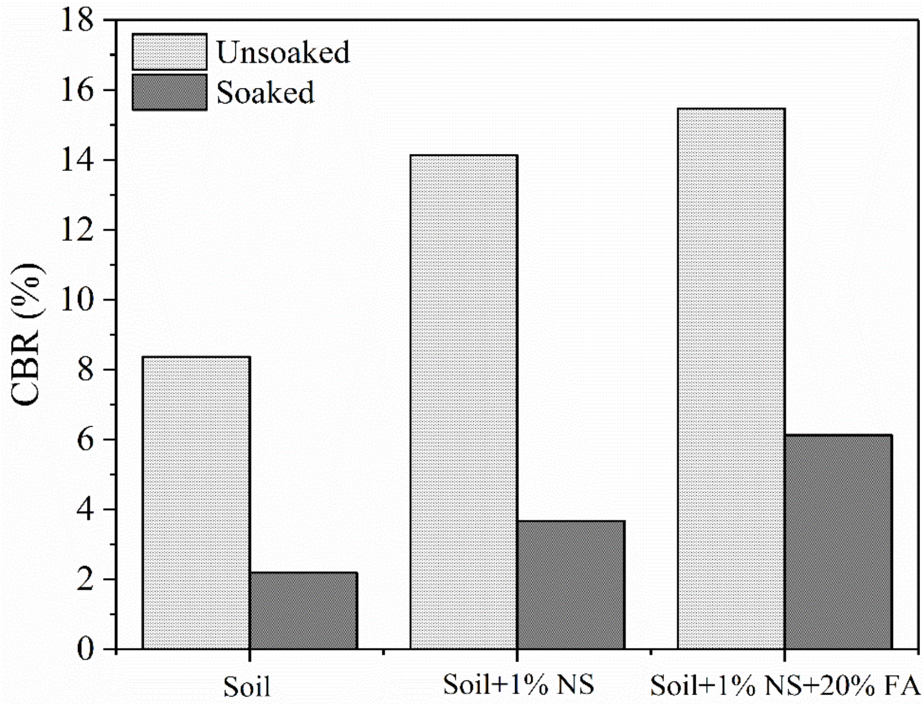


Fig. 5.13. CBR value of Soil (Unsoaked/Soaked), Soil+1% NS (Unsoaked/Soaked), and Soil+1% NS+20% FA (Unsoaked/Soaked).

5.11 SUMMARY

The geotechnical characteristics of the untreated clayey soil and the clayey soil treated with the combination of fly ash and nano silica have been determined using different Indian standards. Additionally, the possibility of conducting a static triaxial experiment with the proposed arrangements has been investigated. The results illustrate the effectiveness of adding fly ash and nano silica with clayey soil as a sustainable solution that can be employed in construction applications and summarized the significant engineering characteristics of these composite materials. The fly contains a larger amount of sand (76.02%), followed by silt (23.52%) and clay (0.44%). The soil has 1.3% sand, 66.67% silt, and 32% clay. According to the Unified Soil Classification System, fly ash is categorised as silty sand (SM), whereas clay soil is categorised as clay with high plasticity (CH). The inclusion of fly ash and Nano-SiO_2 increased the shear strength of the specimens. The optimum shear strength was achieved with 1% Nano-SiO_2 and 20% fly ash. The addition of fly ash and Nano-SiO_2 resulted in the formation of calcium silicate hydrate (C-S-H) and calcium aluminate silicate hydrate (C-A-S-H) gel due to cementitious and pozzolanic reactions, which increased the strength of the soil matrix. For high plastic clay soil, it is recommended that the present combination of optimum value of nano silica and fly ash can be used for subgrade of rural roads.