CHAPTER- II

REVIEW OF LITERATURE

2.1 INTRODUCTION

The high plastic clay deposit presents the biggest challenge to the safe and cost-effective design of geotechnical projects and infrastructure. This kind of soil, which is typically considered to be problematic soil in the field of geotechnical engineering, has unpleasant strength qualities that lead to underlying issues in a variety of construction projects. This type of clay frequently has high compressibility, low permeability, low strength, and high initial water content. Furthermore, many soil deposits like weak soils are only acceptable for construction after adequate treatment, whereas some good soil deposits are suitable in their original state. It is necessary to excavate, modify, or otherwise change the clay soils before they can support the loads that the superstructures place on them. For thousands of years, stabilizing the problematic soil with various stabilizing agents has been considered to be one approach to enhance the strength characteristics of soil (Firoozi et al. 2017). In recent decades, chemical soil stabilization techniques have become widely used due to its benefits for the economics, environment, and engineering properties. For instance, it can be costly and time-consuming to replace poor-quality soil with better-quality soil (Edil et al. 2006; Maaitah 2012). The process of chemical soil stabilization involves the use of different kinds of stabilizers with broad binding properties. These stabilizers fall into three categories: industrial byproducts, conventional stabilizers, and traditional stabilizers (Milburn and Parsons 2004; Firoozi et al. 2017).

Table 2.1 depicts the basic geotechnical characteristics of Indian problematic soil. Annually, thermal power plants burn a significant amount of coal for the production of electricity. These plants generate a lot of fly ash from their air pollution control systems. Some fly ashes have been used to partially replace Portland cement in concrete, despite the fact that the majority are disposed of in landfills. (Energy statistics India, 2021). Table 2.2 depicts the basic geotechnical characteristics of fly ash from various Indian Thermal Power Plants. However, in the interest of sustainable construction materials, environmental regulations in many states have encouraged the reuse of fly ash and several other industrial pollutants. Fly ash can be used as a mineral filler in asphalt paving mixtures, as well as an embankment or filler, stabilising agent for soil or aggregate, and as a filler and/or cement in flowable fill (ACAA 1999; MOEF 1999). Fly ash is an ideal option for fill material because of its higher shear strength and lower specific gravity. The pozzolanic property, the concentration of free lime, and the coarser, inert particle state are responsible for its utilization in soil stabilization (Sivapullaiah et al. 1996). The cost of fly ash is often lower than that of more traditional binder types like cement. Being a by-product of burning coal, it can easily obtain from power plants and the only expense is transportation. Utilizing fly ash for soil stabilisation encourages the reuse of a waste material that would otherwise be dumped in a landfill. This not only reduces the need for raw materials but also encourages environmental sustainability (Ahmad et al. 2024).

Numerous geotechnical engineering experts have investigated the impacts of different types of nano materials to the soil, demonstrating the improved behaviour and increased strength of these treated soils. Few researchers have emphasised a thorough investigation on the basic characteristics of soil treated with various nano materials and their effects on the strength characteristics of soil (Krishnan and Shukla 2019; Chaudhary et al. 2024). The applicability of Nano-SiO_2 (NS) as a soil stabilizing agent has been thoroughly investigated, taking into account current research trends in material characteristics, manufacturing, mixing, and geotechnical aspects. Additionally, the practical mechanism underlying the strength gain has been taken into consideration (Kannan and Sujatha 2022). The objective of the current study is to evaluate the applicability of fly ash and Nano-SiO_2 as a viable stabilizing agent to enhance the strength characteristics of the high plastic clayey soil in seismic prone areas. Consequently, research on the static and dynamic characterisation of clayey soil stabilized with fly ash and Nano-SiO_2 have been focussed here.

This chapter provides a comprehensive explanation of the earlier research efforts that were carried out by several researchers. It includes the brief descriptions of the fundamental geotechnical and dynamic characteristics of the soil stabilized with fly ash. Furthermore, the static and dynamic characteristics of the soil stabilized with Nano-SiO_2 have also been discussed.

Table 2.1. Basic geotechnical characteristics of Indian problematic soil.

Location	Type of soil	IS/USCS Classification	Sp. Gr. (G)	Gravel	Sand	Silt	Clay	LL (%)	PL (%)	PI (%)	OMC (%)	MDD (kN/m^3)	UCS (kPa)	References
Hiriyur Taluk (Karnataka)	Black cotton soil	CH–MH	2.71	0	5	42	53	72	41	31	22	16.5	160	Naveena et al. 2017
Kalinagar (Assam)	Peat	NA	1.9	0	NA	NA	NA	68.4	59.81	8.59	46.53	9.6	10	Paul and Hussain 2020
Coimbatore (Tamil Nadu)	Clayey soil	MH	2.64	0	33.3	38.57	28.13	64	34	30	28.73	14.2	250 (7days curing)	Sudhakaran et al. 2018
Tilda (Chhattisgarh)	Clayey soil	NA	NA	0	NA	NA	NA	42.25	18.6	23.65	13.5	17.2	37	Thomas et al. 2018
Belgaum (Karnataka)	Black cotton soil	CH	2.67	0	6	31	63	72.1	31.7	40.4	32.5	13.4	312.04	Jha and Sivapullaiah 2020
Ranchi	Clayey soil	CL	2.63	0.22	13.16	74.49	7.45	34.79	20.44	13.34	17.81	17.7	24.73	Sharma et al. 2012
Vellode (TN)	Clayey soil	CI	2.57	0.4	25.5	31.2	42.9	39	24	15	14	16.9	94	Kulanthaivel et al. 2020
Nalgonda (Telangana)	Clayey soil	CH	2.59	52	20	32	1	27	72		24.6	16.5	185	Syed et al. 2020
Kadavanthra (Kerala)	Soft clay	CH	2.5	0	15	39	46	91	33	58	28.5	14	28	Thomas and Rangaswamy 2020

Table 2.2. Basic geotechnical characteristics of fly ash from various Indian Thermal Power Plants.

Location	IS/USCS Classification	G	Sand	Silt	Clay	C_u	C_c	OMC (%)	MDD (kN/m^3)	c (kPa)	ϕ (°)	References
Neyveli (Tamil Nadu)	ML	2.55	27	70	10	3.16	1.04	62.3	8.9	16-96	26-39	Pandian 2004
Korba (Chhattisgarh)	ML	1.98	34	63	3	6	1.14	33	1.134	22	34	Sridharan et al. 1998
Rae Bareli (Uttar Pradesh)	ML	2.01	34	65	1	NA	NA	20.6	13	23	34	Sridharan et al. 1998
Badarpur (UP)	SM	2.18	10	87	3	6.3	1.1	38.2	10.6	NA	NA	Mir and Sridharan 2013
Satpura (MP)	NA	1.73	69	25	6	NA	NA	44.24	94	15	29°21′	Prabakar et al. 2004
Kakatiya (Telangana)	ML	1.86	28.13	71.86	0	3.6	1.87	19.82	12.9	42.47	37.02	Reddy et al. 2018
Titagarh (West Bengal)	NA	2.11	82.17	16.83	1	2.22	4.54	41	10.24	NA	39	Sengupta et al. 2017
Ranges of coal fly ash	MI-ML	1.95-2.55	27-34	61-70	1-10	1.59-6.00	0.61-2.47	20.6-62.3	8.9-13	16-96	26-39	Pandian 2004

2.2 STATIC CHARACTERIZATION STUDIES OF SOIL STABILIZED WITH FLY ASH

The research on fine-grained soil stabilized with fly ash was collected and critically reviewed. The literature has been thoroughly examined in terms of its geotechnical characteristics.

2.2.1 Effects of Fly Ash on Atterberg Limits of Soil

When constructing embankments, foundations, and other construction projects, geotechnical engineers use the Atterberg limits to categorize soils into various consistency states and evaluate the possible behaviour of soils under various moisture conditions (Syed et al. 2020). The plasticity Index shows the range of water content at which the soil is in a plastic state. As the fly ash content increased in the expansive soil, the liquid limit (LL) decreased, and the plastic limit (PL) increased. When the fly ash content was 20%, the plasticity index (PI) declined by approximately 50% (Phani Kumar and Sharma 2004). The water content required to make the mix fluid reduces when the silt-sized fly ash particles replace the expansive clay particles. Consequently, the LL falls. Moreover, the pozzolanic properties of fly ash generate flocculation, which increases the size of the blend's particles and lower the water content needed to make the blend fluid. Flocculation may also have contributed to the modest increase in PL. When the Fly ash level increased from 0 to 30%, the PI dropped from 55 to 10.5%, indicating very little plasticity (Phanikumar and Nagaraju 2018). As the amount of fly ash (FA) classes F and C increased, the LL and PI of the clay declined. Class C FA has a greater impact on the change in consistency limits than that of the class F. The explanation could be that class C FA contains more lime than that of class F, which promotes more flocculation, pozzolanic processes, and cation exchange (Seyrek 2018; Shirkhanloo et al. 2021). The diffuse double layer (DDL) theory indicated a drop in the PI of the FA and lime stabilized clay. The engineering characteristics of clay are significantly influenced by the water thickness in DDL. As DDL thickness increases, the plasticity of clayey soil rises. Numerous high-valent cations are present in FA and lime. As the concentrations of high-valent cations within the DDL increases, the layer becomes thinner and PI of the clay matrix reduces (Sivapullaiah et al. 1996; Zha et al. 2008; Zhou et al. 2019). As the FA content in the soil composite mixture increased, the LL, PL, and PI values decreased slightly, despite the fact that the FA component of the mixture was not plastic (Sengul et al. 2023).

2.2.2 Effects of Fly Ash on Compaction Characteristics of Soil

Soil compaction refers to the process of densification and exhibits relative variance in their mechanical and physical properties. For all earthwork constructions, controlling field compaction is crucial. This involves evaluating the laboratory compaction parameters including maximum dry density (MDD) and optimum moisture content (OMC). In order to achieve a high density and minimum intergranular voids, proper compaction of the fill material is essential for constructing earth-dams, road embankments, railway subgrade, or compacted clay liners for garbage disposal (Shimobe and Spagnoli 2020). One of the most important steps in the construction of earthworks is field compaction. It involves by applying compactive force on the soil particles to bring them closer to one another, increasing the shear strength of soil and decreasing its permeability and compressibility (Gurtug and Sridharan 2004). The OMC and MDD declined as the FA content in the soil matrix increased. Since fly ash is a lightweight material, it replaced the expansive clay in the blends and the MDDs decreased. Furthermore, as fly ash would replace more clay particles, in fly ash-clay composite mixture with greater fly ash contents, less water would be needed to produce MDD. As a result, OMCs dropped as fly ash content increased (Phanikumar and Nagaraju 2018). With an increase in FA and FA-lime content, there was a drop in both the OMC and the maximum dry unit weight. The reason for the decrease in the OMC is that with the increase in fly ash concentration there is reduction in the electric double layer thickness due to the cation exchange between the stabilizing agent and expansive soil, which encourages flocculation. The maximum dry unit weight decreased as the amount of fly ash and lime-fly ash increased. This was mostly because the material had lower specific gravity than that of the expansive soil and cemented product formed quickly, which decreased the density of treated soil (Zha et al. 2008). The MDD of soil decreased as the FA and limestone dust content increased, but the OMC displayed the opposite pattern. The cation exchange reaction causes the flocculated and agglomerated soil particles to occupy larger areas, which increases the volume of voids and decreases MDD. The reason for the increasing OMC with FA and limestone dust could be because the soil-additive mixture has an affinity for more water to finish the cation exchange reaction (Brooks et al. 2011). As the percentages of cement and FA in the cement-FA stabilized black cotton soil increased, the MDD values dropped. The reason could be that lighter FA particles have replaced the more substantial soil particles. A little increase in OMC was noticed with an increase in the cement percentage due to the hydrophilic nature of the binder. Thus, the OMC of soil-cement mixtures depends on both the amount of cement and the plasticity characteristics of the soil. The initial decrease in OMC at lower stabilizer dosages was followed by an increase due to the water demand of the mixes to meet the hydration of cement and lubrication of finer FA particles (Chethan and Shankar 2021). The MDD declined as the FA content in the control sample increased, but overall OMC increased. An increase in fines, which have a lower specific gravity and fill in the soil's voids, may be the cause of the drop in the MDD. The affinity of water resulting from the accumulation of these recently introduced particles may be the cause of the rising OMC from the rise in FA concentration (Renjith et al. 2021).

2.2.3 Effects of Fly Ash on California Bearing Ratio (CBR) of Soil

The California Bearing Ratio (CBR) is the most often utilized parameter for designing the flexible pavements in tropical regions. Pavement thickness is mostly determined by the bearing capacity of the subgrade soil. Low CBR is correlated with thicker pavement, and vice versa. For a given compactive energy of the soil matrix, soil samples are compacted at a MDD and predetermined OMC in order to determine the representative CBR. The CBR increased by approximately 80% and 37%, respectively, in the presence of 7.5% and 15% FA for the soil-FA composite mixture treated with an enzyme additive. The inclusion of the enzyme additive, which neutralizes the negatively charged clay molecules, can be connected to the improvement in load carrying capacity by reducing their affinity for water (Karami et al. 2021). After 7 days of curing, the class F stabilized specimens have a CBR of 6.1% to 22.8%, and the class C stabilized specimens have a CBR of 9.6% to 32.7%. The interaction between the CaO present in FA and the SiO_2 and Al_2O_3 present in the soil led to the creation of a resistant gel of hydrated calcium silicate and hydrated calcium aluminate, which in turn increased the CBR (Shirkhanloo et al. 2021). As the quantity of FA and sludge ash increased, the CBR values of soft subgrade soil increased. The CBR values were greater than 10 for fly ash and soil specimens in all fly ash addition amounts, and the rise in CBR values was nearly constant at low additive amounts (2% and 4%). This finding suggests that soft subgrade soil can be improved by both sludge ash and fly ash, and that the degree of improvement rises as the amount of ashes increases (Lin et al. 2007). The CBR values of the soil treated with a mixture of 15% FA and 3% limestone dust were approximately 170% higher than those of the untreated soil. The development of cementitious gel as a result of the pozzolanic reaction of the soil-additive combination and specific cation exchange, flocculation, and agglomeration reactions could be the causes of the rise in CBR with the ash concentration (Brooks et al. 2011). The inclusion of fly ash and the stabilizing impact of cement on the two soils resulted in increased CBR values of sand-fly-ash-cement mixes that were generally higher than those of lateritic soil-fly-ash-cement mixes. This difference was greatest at fly ash levels of 50 and 65% (Singh and Kalita 2013).

2.2.4 Effects of Fly Ash on Strength Characteristics of Soil

The Unconfined Compressive Strength (UCS) of soil is a crucial and significant geotechnical property that is frequently employed as an input parameter for the planning and execution of different civil engineering projects. The UCS measures the strength and load bearing capacity of the soil to regulate its deformational behaviour (Sharma and Singh 2018). A number of researchers noticed an increase in UCS after treating the soil with fly ash (Puppala et al. 2001; Solanki et al. 2009; Brooks et al. 2011). The compressive strength of the soil was improved by the inclusion of class C and F fly ashes as well as the curing period. It seems that 25% is the optimal FA percentage for both types of FA. Furthermore, it was discovered that class C FA performed significantly better than class F FA in increasing the soil's compressive strength. This could be because the class C FA contains a non-negligible amount of lime, which has the ability to self-cement. Class C FA also contains anhydrite, which when combined with water forms gypsum, which also has binding properties. Conversely, class F FA has a low calcium content, which means it lacks sufficient cementitious characteristics and has little effect on strength of the soil (Seyrek 2018;

Shirkhanloo et al. 2021; Turan et al. 2022). Although fly ash has some cementing properties, studies indicate that fly ash alone cannot sufficiently improve the geotechnical properties for usage in pavement and foundation design. However, there have been some reports in the literature that fly ash can be used effectively, particularly when mixed with other additives (Sharma et al. 2012). Despite the fact that a number of alternative combinations, including fibres, rice huck ash, and ground granulated blast furnace slag (GGBFS) mixed with fly ash, have also been shown to adequately strengthen problematic soil (Sharman and Sivapullaiah 2016; Phanikuma and Nagaraju 2018; Sengul et al. 2023), for the majority of stabilization projects that have been completed to date, cement and fly ash are still the primary components (Kaniraj and Havanagi 1999; Kolias et al. 2005; Cristelo et al. 2013; Yazıcı and Unsever 2024). It takes some time to significantly increase the strength because this is the induction time required for the chemical pozzolanic interactions between lime and fly ash to occur and create a new cementitious phase. Furthermore, the temperature of curing has a significant impact on the delay period. After 180 days of curing, the soil-fly ash-lime composite mixture and soil-lime showed compressive strength values of 7 and 2 MN/m^2, respectively (Consoli et al. 2001). The strength of soil-fly ash-sawdust ash mixes declined when the binder concentration was increased beyond 15%. Thus, it was determined that the optimum dosage for soil-fly ash-sawdust ash was 15%, which increased strength from 146.33 kPa to 355.20 kPa. The UCS of soil-fly ash-sawdust ash mixes was further improved by the addition of cement (Mohamed et al. 2023). A high SO_3 level is indicated by a high CaO content in FA. When the curing temperature is raised, up to 85^oC, the presence of SO_3 concentration will result in the creation of ettringite and delayed expansion, both of which will adversely affect the stability of the soil. However, significant variations in soil temperature are uncommon. Increasing the fly ash concentration increased the UCS values because it increased the contents of CaO, SiO_2, and Al_2O_3, irrespective of changes in the curing period and applied compaction energy. The specimens that were cured for 28 days showed higher increases in UCS values as compared to those that were cured for just one day (Yilmaz et al. 2019). Depending on the type and composition of fly ash, an activator may be used with it. Fly ash is believed to contain self-cementing characteristic. Nevertheless, fly ash cannot be used alone for soil stabilization because it has very little CaO and does not have the same self-cementing properties as that of the other soil stabilizers. A pozzolanic reaction, however, can be carried out by combining fly ash with an activator, such as cement or lime. Consequently, a substantial amount of cementitious gel will be formed in order to enhance the strength (Arora and Aydilek 2005). When the strength development outcomes of using only fly ash and fly ash along with Portland cement were evaluated, it was discovered that the strength of soil treated with the fly ash-cement blend would be lower than the usage of cement alone. The cement-soil mixture nearly matched the maximal strength growth at a longer curing period when compared to 50% cement and 50% fly ash. Because the maximum strength gain was almost identical over longer curing times, it was therefore preferable to utilize a fly ash-cement blend rather than cement alone. The pH and PI value of the stabilized soil were important factors in determining the soil-stabilizer mixture's UCS. The treated soil sample showed a lower compressive strength if the PI value was larger. With pH, however, the situation was the exact reverse. The larger pH value of the treated specimens will cause more silica and alumina being soluble in clay minerals, increasing the amount of cementitious gel that was created during the pozzolanic reaction, which gives the soil strength. This will raise the compressive strength of the specimens (Mahedi et al. 2020). The inclusion of

3% limestone dust and 15% FA to the untreated soil sample resulted in a significant rise in UCS. All soil-additive mixes had higher UCS values at both early and later ages compared to the untreated soil sample. The primary factor contributing to the soil-additive mixture's increased strength is the pozzolanic activity of the limestone dust and fly ash in the composite mixture, which creates a cementing gel that holds the soil aggregates together (Brooks et al. 2011). The maximum UCS value of the CH soil was obtained with the combined addition of 12% FA, 8% GGBS, and 6% lime and curing for 7 days. The UCS of the stabilized material improved dramatically with increasing compaction effort (Maneli et al. 2016). To improve strength in expansive soil, it's useful to know the ratio at which fly ash will be added to replace some of the stabilizer that's being partially replaced. The pozzolanic material present in the clay particle in Calcium Carbide Residue (CCR) stabilized clay will naturally react with the Ca $(OH)_2$ that the CCR provides. As CCR rises, the content of Ca $(OH)_2$ will also rise. A point is achieved when increasing the CCR content no longer results in an increase in strength. This is because of the unsoundness of the free lime, which remains unreacted, a subsequent increase in CCR causes a fall in strength rather than an increase. If more pozzolanic material is supplied at this point, like fly ash, the pozzolanic interaction between free lime and fly ash will continue (Horpibulsuk et al. 2012). The research findings demonstrated that red mud, lime, and phosphogymsum were excellent choices for activating low lime fly ash; the strength improvement from mixing these materials with fly ash was significantly more than that from utilizing fly ash alone. The increased calcium hydroxide that the phosphogymsum and red mud provide results in stronger CSH gel formation over longer curing periods (Kim et al. 2019). The UCS increased after seven days with the addition of fly ash, construction demolition (C&D) waste, and lime. When compared to fly ash and C&D waste, lime has a greater strength gain; however, there was very little strength difference when lime and C&D waste were added together. Consequently, C&D waste can be used to stabilize soil, even though lime costs a little more. The addition of fly ash resulted in a much higher increase in 28-day strength when compared to the addition of C&D waste and lime. Therefore, fly ash can be utilised for soil stabilisation when the primary requirement is long-term strength and the secondary requirement is short-term strength gain (Sharma and Hymavathi 2016).

2.2.5 Effects of Fly Ash on Durability Characteristics of Soil

The durability of a geotechnical material is determined by how effectively it resists freeze-thaw cycles and wet-dry cycles. Wetting-drying cycles should be carried out in all geographical areas, however freeze-thaw tests should only be carried out in places that are susceptible to freezing temperatures, such as cold regions (Zhang and Tao 2008). The main factors that determine durability are temperature and moisture content. The long-term performance of binder-soil combinations can be predicted from these types of field-related circumstances. Wetting-drying (W-D) and freezing-thawing (F-T) methods are used in the laboratory to simulate the durability characteristics described in ASTM D559/D559M-15 and ASTM D560/D560M-16, respectively. Soil stabilized with cement was unable to withstand degradation during W-D cycles. Because of the quick moisture absorption during the wetting cycles that followed the drying cycles, there was an abrupt loss of soil. As a result, the mixtures' integrity was subjected to more severe W-D durability testing. Degradation by W-D cycles was successfully inhibited in stabilized soil treated with a high proportion of fly ash and 10, 12, and 14% cement. A weight loss of less than 14% was achieved by the majority of the stabilized mixtures after 12 F-T cycles (Chethan and Shankar 2021). Fly ash stabilized soils lost up to 40% of their strength as a result of freeze-thaw cycles; whereas, wet-dry cycles had almost no effect on stabilized soils. Even after being drastic reduction in strength, the stabilized soils were still at least three times stronger than the unstabilized soils (Bin-Shafique et al. 2010). The ageing effects of thawing-freezing and immersion in water may weaken the stabilized soil, although varying binder types and contents result in varying rates of change. Class-F fly ash helps to make high-volume fly ash potentially useful for soil stabilization, but at relatively small addition levels, it cannot increase resistance to thawing-freezing and water immersion. Although cement performs worse when considering the coefficient of strength loss, it performs better than lime in UCS values (Wang et al. 2018). The compressive strength of 7-days cured specimens treated with fly ash and cement increased as the number of F-T cycles increased. The increase in strength with the number of cycles was more noticeable for mixes containing 7% cement compared to mixtures containing 4% and 5% cement. The damage that the fly ash and cement-treated cohesionless specimens sustained from ice lenses inside their pores during freezing was minimal. Conversely, the durability of the specimens was negatively impacted by the presence of kaolinite. Likewise, specimens treated with lime were able to withstand freezing and thawing, but as the number of freeze-thaw cycles increased, their strength reduced. When cohesive particles were present in the specimens, the negative impact was more noticeable (Arora and Aydilek 2005). Dispersive soil specimens perform better in F-T cycles and during water immersion when cement clinker, GGBS, and fly ash were added. With the rise in number of F-T cycles, the UCS values were noticed to be increased at 7, 14, and 28 days of curing. However, at the 60- and 90-days curing, the strength somewhat declined. The effects of GGBS and class F fly ash on water immersion ageing and freezing-thawing damage were not significant. Blending fly ash treated soil, GGBS, and cement clinker together yields a superior result than using each component separately (Mohanty et al. 2021). A decrease in strength was observed in the fly ash and saw dust ash-treated soil, as the bond between the CSH and CAH gels becomes weaker with the increase in D-W cycles. After one cycle, the strength dropped from 588 to 478 kPa; after two cycles, it dropped to 351 kPa; and after six cycles, it dropped to 100 kPa. However, as the curing period increased, the specimen became more brittle, which may have been caused by the formation of dense hydrates. This is in contrast to the UCS, which also increased with the curing period and the peak strain at failure (Mohamed et al. 2023). A significant reduction in the UCS value of the subgrade was found upon freezing and thawing cycles. The pozzolanic reaction caused the fly ash stabilised soil samples to have a significantly higher shear strength than the natural soil samples. However, the shear strength of the soil samples with 10% and 20% fly ash added decreased as a result of F-T cycles. Although the inclusion of polypropylene fibre strengthened the soil mixtures, it was insufficient to counteract the loss caused by the F-T cycles (Sengul et al. 2023). The moduli of silty clay declined as the number of freeze-thaw cycles increased, and the rate of change under dynamic loading frequencies of 32 Hz, 42 Hz, and 52 Hz, respectively, are 20.58%, 19.09%, and 17.75%. Nonetheless, there was some volatility in the modulus of the silty clay modified by fly ash and crumb rubber following the F-T cycle. The results revealed that the addition of fly ash and crumb rubber reinforced the modified soil matrix and increased its cohesiveness (Wei et al. 2015).

2.2.6 Microstructural Characterization of Soil Stabilized with Fly Ash

It is necessary to have a thorough understanding of the microstructural behaviour of clayey soil in order to understand the physicochemical changes that take place both before and after the chemical stabilization. A range of microstructural characterization tests are generally performed on the untreated and fly ash-treated soil at varying curing times using X-ray diffraction (XRD), stereomicroscopy, Fourier transform infrared (FTIR), thermogravimetric analysis (TGA), scanning electron microscopy, and energy dispersive X-ray spectroscopy (SEM/EDS). These tests are conducted to measure the stages and morphological alterations that takes place by the cementitious product in the soil mixture containing fly ash. Furthermore, the mechanical properties of soil, such as volumetric stability, bearing capacity, and shear strength, can be significantly influenced by the microstructure of a material, which includes particle size, molecular bonding, element compositions, and mineral compositions. The way that these materials are used in construction is therefore determined by these characteristics. The microstructural studies enable the complete recognition of fly ash-clay particle interaction based on pozzolanic processes and the spread of soil surface cracks. The chemical composition of the materials can be inferred qualitatively using FTIR and XRD tests. Additionally, stereomicroscopy provides qualitative details regarding the physical properties of the material. To acquire quantitative data on fly ash mixed soils, the EDS analysis is done in conjunction with SEM. The effects of fly ash on the microstructure and strength development of silty clay stabilized with cement was determined by TGA, SEM, and mercury intrusion porosimetry (MIP). They noted that fly ash, a non-interacting material, splits the massive cement-clay clusters into smaller clusters with reduced pore space (Horpibulsuk et al. 2009). The edges of the particles attacked by lime are visible in the SEM of the clayey soil with 3% lime and 15% fly ash, which explains the ragged look observed in the micrograph. Furthermore, the flocs were coated with a gel-like substance that seems to bind the individual particles together. In the SEM pictures, it was discovered that the treated soil layers had different cementitious gel morphologies. Additionally, by activating the cation exchange capacity surrounding the clay matrix, the soil's swell potential has been effectively neutralized (Brooks et al.2011). The expansive properties of the soil were attributed to the presence of montmorillonite, a mineral that was validated by the EDS analysis. The presence of montmorillonite mineral was indicated by a broad peak at 8.96° in the untreated soil, which sharpened with the addition of fly ash and lime, indicating the breaking of the montmorillonite structure. The XRD charts further show that the pozzolanic reaction is responsible for stabilization, as evidenced by the absence of the peaks at 28.48° and 14.00° in the untreated soil and the development of those peaks in the stabilized soil with fly ash and lime, which indicated the generation of CSH and CAH gel. The production of CSH and CAH gel as well as the breakdown of the montmorillonite mineral in the untreated soil were also confirmed by the TGA data. The development of new cementitious compounds as a result of the pozzolanic reaction was demonstrated by the SEM images, which also indicated that the radius of the pore spaces had decreased (Sharma et al. 2012). According to SEM images, it was observed that the kaolinite particles firmly surrounded the fly ash particles. The surface of the huge fly ash particle has small kaolinite particles adhered to it. The inclusion of the organic polymers caused the kaolinite to aggregate in comparison to unmodified fly ash–kaolinite combinations, producing a dense microfabric (Kang et al. 2019). The relative dominance to a disturbance in the matrix is confirmed by the XRD results of cement clinker, fly ash, and GGBS treated dispersive soil. Some new cementitious compound peaks are formed, and the peak intensity of quartz and montmorillonite decreases with the increase in curing period. These results indicate the creation of CAH, CASH, CSH, CSHH, and CAOCH gels as well as the hydration of reactive minerals and the glassy phase. These cementitious gels diminish the void spaces and bind and cover the individual soil particles, resulting in a hard structure.

The SEM pictures, on the other hand, depict a better interface state and reveal that the treated soil specimens have reorganized their orientated structure into a more flocculated structure with no sign of pore formation. The soil-binder combinations that contain cement clinker exhibit more noticeable formation of hydrated grains, a dense structure, a compacted and cemented matrix, and the creation of a flocculated structure (Mohanty et al. 2021).

2.3 STATIC CHARACTERIZATION STUDIES OF SOIL STABILIZED WITH NANO SILICA

The research on fine-grained soil stabilized with Nano-SiO_2 was explored and critically reviewed. The literatures have been thoroughly examined in terms of their geotechnical characteristics.

2.3.1 Effects of Nano-SiO_2 on Atterberg Limits of Soil

With an increase in Nano-SiO_2 in the soil matrix, both LL and PL increased. However, LL increased more slowly than PL, which led to a drop in PI. The silica nanoparticles exhibit strong reactive surface charges and a large specific surface area, which lead to the development of interparticle interactions and their increased water retention capability. This alters the amount of moisture absorption and reduces the plasticity of the clay (Kalhor et al. 2019). Similar observation was noticed by Kalhor et al. 2022 that as the Nano-SiO_2 % increased, the values of LL and PL also increased. Adding additional Nano-SiO_2, however, causes the PL to increase more than the LL, which lowers the PI value. All samples showed a decline in plasticity index as the curing time increased, with the sample containing 1% Nano-SiO_2 showing the greatest changes. This could be caused by short-term reactions and a thin coating of Nano-SiO_2 particles surrounding the active surface of clay particles. After 28 days of curing, 1% Nano-SiO_2 was added to dispersive soil, reducing PI from 23% to 14%. Higher concentrations of Nano-SiO_2 resulted in a rise in PI values; following a 28-day treatment, the PI of samples containing 1.5 and 2% Nano-SiO_2 was equal to 16 and 17%, respectively. Since the inclusion of Nano-SiO_2 improves the workability of the stabilized clay, the PI reduction of the dispersive soil samples can be considered as a positive development (Vakili et al. 2020). The consistency limits of loess stabilized with 10 and 29 nm Nano-SiO_2 increased with the increase in Nano-SiO_2 concentration, while those of loess stabilized with 100 nm Nano-SiO_2 significantly reduced. Because the aggregate pore water is difficult to disperse during the consistency test procedure, the LL and PL of the Nano-SiO_2-stabilized loess are higher (Lv et al.2018). The LL was raised by mixing Nano-SiO_2 with the dispersive clay. In addition, PL increased as the amount of Nano-SiO_2 in the treated specimens increased; however, this increase was occurring at a slower rate than that of the LL, resulting in a drop in PI in the specimens even after 1% of Nano-SiO_2 was added. The change rate in consistency limits would be slowed down in specimens with 1.2% and 1.5% Nano-SiO_2. This indicates that the properties of plasticity are not significantly affected by increasing the Nano-SiO_2 content over 1%. This can be explained by the fact that nonhomogeneous mixtures are caused by a greater increase in the content of Nano-SiO_2 (Masrour et al. 2021). When soft clay with Nano-SiO_2 particles was mixed at different concentrations of 0.5%, 0.7%, and 1% by weight of soil, it was shown that the reduction in LL and increase in PL led to the declination of PI. Additionally, shrinkage limit (SL) dropped proportionately to the amount of Nano-SiO_2. In comparison to natural clay, the largest drop in LL was 11.5% at a dosage of 0.7%; below that, a less noticeable reduction was observed. Thus, it was determined that 0.7% was the optimum dosage. It was revealed that 52% of the plasticity was reduced at the optimal nano-content of 0.7%. The interparticle force between soil particles was strengthened by the nano additive, lowering the shrinkage limit. More bonding was provided by the viscous gel that the soil and additive created than by the water that was adsorbed. The frictional resistance was enhanced and the interfacial contact surface area was raised due to the reduction in interparticle spacing (Changizi and Haddad 2017). There was only a modest increase in the LL and PL after adding Nano-SiO_2 (0.5–3%) to lacustrine highly compressible clay. The increased in the consistency limits could be caused by the water absorbed by Nano-SiO_2 (García et al. 2017).

2.3.2 Effects of Nano-SiO_2 on Compaction Characteristics of Soil

The optimum moisture content (OMC) of the treated soil specimens increased as the concentration of silica nanoparticles in the soil increased, while their dry unit weight decreased. This can be attributed to the Nano-SiO_2 large specific surface area, which increased the water-holding capacity and, consequently, the OMC of the specimens. Additionally, the specimens' dry unit weight is lowered because Nano-SiO_2 has a lower specific gravity than the soil (Kalhor et al. 2019). The treated samples' MDD decreased and their OMC increased as a result of the nanoparticle addition. The reason for this is that when nanoparticles are present, cementitious materials like CSH gel quickly develop, decreasing the compatibility and density of the soil treated with silica nanoparticles. Furthermore, the addition of Nano-SiO_2 to the sample results in the flocculation and agglomeration of the soil particles as well as the formation of easily filled macropores that increase the optimal moisture content (Vakili et al. 2020). The test results showed that increasing the amount of Nano-SiO_2 in the base soil decreased its MDD and raised its OMC. Smaller size of silica nanoparticles, which have a specific gravity lower than soil particles, will occupy these void spaces. As a result, the treated samples had a reduced density due to the presence of particles having a lower specific gravity per unit volume. Additionally, as the cation exchange process in the soil structure advances as a result of the addition of silica nanoparticles, more water molecules are involved in the chemical reaction. In other words, the Nano-SiO_2 additive has a high absorption capacity due to its larger surface charge and greater specific surface area. Thus, more water is required to obtain the OMC (Masrour et al.2021). An increase in the amount of Nano-SiO_2 stabilized soil resulted in an increase in both the maximum dry unit weight and the optimal moisture content. The OMC raised by factors 1.1, 1.14, and 1.2 and the maximum dry unit weight increased by factors 1.05, 1.1, and 1.13 for Nano-SiO_2 contents of 0.5, 0.7, and 1.0 % respectively. The OMC of the stabilized soil increased as a result of the action of moisture absorbed by Nano-SiO_2. Additionally, Nano-SiO_2 fills the spaces between clay particles in the soil, reducing the void ratio of the soil mass and raising the maximum dry unit weight of the stabilized soil (Changizi and Haddad 2016).

2.3.3 Effects of Nano-SiO_2 on Strength Characteristics of Soil

The compressive strength increased when up to 1% of Nano-SiO_2 was added to the dispersive soil during the curing process. The strength enhanced in the presence of Nano-SiO_2 because its particles have filling properties that eliminate soil pore spaces. Higher concentrations of Nano-SiO_2, however, negatively impacted the samples and decreased the compressive strength. The lack of reactivity between soil and Nano-SiO_2 ions is the cause, which could be related to the restricted mobility and insufficient dispersion of the particles. Conversely, samples stabilized with Nano-SiO_2 showed an increase in compressive strength when the curing time was extended. The UCS values were 252 and 611 kPa, respectively, after adding 1% Nano-SiO_2 to the materials after 1 and 28 days of treatment; these results can be explained by finishing long-term chemical processes. Accordingly, 1% of Nano-SiO_2 stabilizer was the optimum amount for compressive strength based on the results, as it showed the best performance in terms of both short- and long-term unconfined compressive strength improvement (Vakili et al. 2020). When compared to the base soil, the treated specimens UCS improved significantly after 7 days of curing with the addition of Nano-SiO_2 in every percentage. The UCS of the treated specimen reached its maximum when the Nano-SiO_2 content was increased to 1%, however the UCS decreased when the additive was increased even higher. Moreover, extending the curing period enhances the strength gain of the treated specimens in a comparable manner. It is evident that as the curing period was extended from 7 to 28 days, the treated specimens UCS improvement rate improved. After 28 days of curing, the highest amount of improvement was obtained with 1% Nano-SiO_2. Furthermore, extending the curing period from 7 to 28 days significantly accelerated the reduction in failure strain. The ability of Nano-SiO_2 to fill in gaps and facilitate early cation exchange between clay and silica particles, as well as the subsequent pozzolanic reaction that forms calcium-silicate-hydrate gel (C─S─H), are the main causes of the treated samples substantial improvement in the UCS (Masrour et al. 2021). The compressive strength of the stabilized soil increased as the Nano-SiO_2 content increased, while the residual strength of the stabilized soil decreased. When the Nano-SiO_2 content increased to 0.7%, the strength grew as well; after that, it decreased. With the addition of Nano-SiO_2, the residual strength of the stabilized soil fell by factors 0.63, 0.58, and 0.48 and the UCS increased by factors 1.3, 1.56, and 1.5 for Nano-SiO_2 contents of 0.5, 0.7, and 1.0 % respectively. This might occur at constant moisture content because of the lack of water in the soil and Nano-SiO_2 mixture from the absorption of water by the Nano-SiO_2. This makes the soil less compressible, which gets worse when the amount of Nano-SiO_2 in the soil is increased. This could be the cause of the decrease in strength of the stabilized soil with 1.0% NS compared to soil stabilized with 0.7% NS (Changizi and Haddad 2016). An increase in strength was noticed for all treated samples with varying curing days at very low Nano-SiO_2 content. On the other hand, there was a noticeable variation in the compressive behaviour of the samples after varying the Nano-SiO_2 content for both short-term (7 days and 14 days) and long-term (28 days and 60 days) curing durations. The ductile behaviour was integrally maintained for the duration of the short-term curing period, with post-peak stress gradually decreasing with strain. This behaviour is similar to that of the untreated sample, which showed changes in peak stress after 1% of the Nano-SiO_2 content and until the Nano-SiO_2 content was greater than 2%. All of the treated samples became significantly more brittle than the untreated samples during longer curing times, such as 28 and 60 days (Kong et al. 2018).

2.3.4 Microstructural Characterization of Soil Stabilized with Nano-SiO_2

The scanning electron micrographs (SEM) of the untreated, 1%, and 2% Nano-SiO_2-treated samples, after 7 days of curing, showed that the untreated soil particles had a dispersed structure and a significantly higher number of pores among them than that of the treated soil. Furthermore, the particles flocculated and fewer of these pores were present when 1% Nano-SiO_2 was added to the soil sample. When soil is supplemented with Nano-SiO_2, the soil undergoes chemical reactions, becomes denser, fills the spaces between the particles, and eventually becomes stronger. When Nano-SiO_2 content is higher than what is considered optimal, it can cause agglomeration of Nano-SiO_2 particles and a lack of their homogenous distribution, which can result in weak lumps in the sample (Vakili et al. 2020). Similar observation was noted by using SEM micrographs, the microstructure of the base soil and the optimum 1% Nano-SiO_2-treated specimen at 7 and 28 days of curing were examined. It was reported that the base soil exhibited a porous structure. When the base soil and the specimen with 1% Nano-SiO_2 content were compared and allowed to cure for seven days, it was discovered that the addition of Nano-SiO_2 caused the specimen's porosity phase to decrease because of the flocculation, agglomeration, and development of the C-S-H gel. The C-S-H gel was clearly filled in the pores after 28 days of curing, indicating that the Nano-SiO_2 reaction with the CaO in the parent base soil had enough time to take the effect (Masrour et al. 2021). When Nano-SiO_2 was added, microstructural evolution with increasing content at the specified curing duration was observed through two low magnification SEM pictures of the untreated and treated loess. The addition of low Nano-SiO_2 content initially led to an observed filled effect in the pores between the particles or aggregations, which decreased the treated loess's porosity and raised its density degree. Subsequently, the treated loess experienced a clear aggregated impact due to the additional rise in Nano-SiO_2 concentration, leading to the formation of larger aggregations. Larger holes and looser packing were seen in the treated loess at very high Nano-SiO_2 content levels (Kong et al. 2018). The fundamental mineral composition of the Nano-SiO_2-stabilized loess remained unaltered, as evidenced by the X-ray diffraction spectra of the material which closely matched that of the compacted loess. Nevertheless, no new XRD peaks had formed, and the diffraction intensity of some minerals had reduced. Analysis using Fourier transform infrared spectroscopy revealed that chain-structured C-S-H and C-A-S-H gels predominate in the reaction product (Lv et al. 2018).

2.3.5 Effects of Nano-SiO_2 and Other Additives on Atterberg Limits of Soil

The different percentages of silica nanoparticles in the residual cement-treated soil did not show any appreciable variations in the LL of the NS-treated soil at any cement level. Conversely, at a 0.2% NS level, the PL of the specimen first increased but then decreased as the Nano-SiO_2 content increased. However, the addition of larger quantities of 80 nm Nano-SiO_2 particles raised the PL at the cement level by 4%. The tendency towards the change was often more notable for the Nano-SiO_2 particles of 15 nm median size. At varying Nano-SiO_2 content, the PL displayed a more consistent value as the cement dose was raised to 8%. At cement doses of 4% and 6%, samples containing 15 nm silica nanoparticles had a lower PL than the samples containing 80 nm silica nanoparticles. The greater packing density and higher surface energy of Nano-SiO_2 may be the cause of the decreased PL observed in the presence of 15 nm silica. However, the PL of samples containing 80 nm silica nanoparticles dropped to a level lower than that of the samples containing 15 nm silica particles as the cement percentage increased to 8%. The greater water absorption in samples containing 15 nm Nano-SiO_2 could potentially be explained by the hydration-accelerating action of small sized Nano-SiO_2 with higher levels of cement (Bahmani et al. 2014). The results demonstrated that, when taking into account the impacts of different percentages of Nano-SiO_2 on the properties of soil treated with cement kiln dust (CKD), the liquid limit values only slightly increase with the NS content increment. Furthermore, the plastic limit was only slightly affected by increasing the NS level. The PL value of the tested soils first increased at 0.5% NS content before declining at a higher amount (2% of NS). Ultimately, the use of CKD and NS caused the treated soil's plasticity index to rise. These effects may be attributed to the large specific surface area (SSA) of Nano-SiO_2, which interacts with other particles in the soil matrix to provide a modest rise in the PI value of the CKD treated soil (Ghavami et al. 2021). When the Nano-SiO_2 concentration increased to 1.2% and the plantain leaf ash content increased to 15%, the LL of the unreinforced soil sample decreased by a factor of 1.5 while the PL decreased by a factor of 1.3. The incorporation of plantain leaf ash and Nano-SiO_2 into expansive soil can effectively decrease its liquid and plastic limits. Plantain leaf ash contains some chemical compounds that enhance the soil's binding capabilities, assisting in structural modification. The ash particles reduced the amount of water required to reach the LL by filling in the void spaces in the soil. Furthermore, Nano-SiO_2 fills in the voids left by larger particles in the soil matrix, reducing the soil's flexibility due to its small particle size. Because the filling effect reduces the soil's ability to absorb water, it lowers the plastic limit (Alshawmar 2024). Adding 1% cement to the soil resulted in a drastic reduction in LL, while increasing the dose of Nano-SiO_2 caused a minor reduction in LL. Even though soil cement had the lowest PL value in the absence of nanoparticles, the values seemed to remain stationary as the recommended amount of Nano-SiO_2 increased (Thomas and Rangaswamy 2020). When the hydrated lime and Nano-SiO_2 were added to the gas oil-contaminated clay, at dosages of 1%, 2%, and 3% by weight of soil for each, both separately and jointly, the results revealed an increase in LL and PL and a decrease in PI as the amount of additives in the soil increased. A decrease in PI signifies increased soil workability. Due to the limitations in the creation of a double diffuse layer, gas oil-contaminated soil alone also raised LL and PL. This resulted in a higher requirement of water to remain in plastic nature. There was more water absorption due to the greater specific surface area of the Nano-SiO_2. On the other hand, the formation of cementitious compounds by hydrated lime led to higher consistency limits since these compounds had a higher capacity to absorb water. Due to the increased pozzolanic characteristics of the additives, the combination of hydrated lime and Nano-SiO_2 required more water to satisfy the cation exchange processes (Nezhad et al. 2021).

2.3.6 Effects of Nano-SiO_2 and Other Additives on Compaction Characteristics of Soil

According to the research on the impact of SiO_2 nanoparticle addition on the compaction characteristics of cement-treated soil at varying cement levels, the addition of nanoparticles increased the specimens' OMC and slightly decreased their MDD. Nevertheless, for all cement levels, the inclusion of nanoparticles with an average diameter of 80 nm was found to increase the MDD more than that of 15 nm. Additionally, it was noted that while the MDD decreased, the OMC increased in response to an increase in the nanomaterial concentration. If the amount of silica nanoparticles is increased beyond the optimal limit, this could lead to the agglomeration of nanomaterial particles, which could raise the OMC and, as a result, hamper dispersion, and reduce MDD (Bahmani et al. 2014). The addition of Nano-SiO_2 decreased the soil's MDD. The mean particle diameter size of the nanomaterial is measured in nanometres, therefore when larger soil grain sizes are partially replaced by very fine nanosized particles, the density of the soil mixes decreases and becomes lighter. This results in a somewhat greater OMC for the soil. Incorporating cement into the soil samples was found to increase the MDD. The reason for this is that when cement and aqueous Nano-SiO_2 are present, a calcium-silica-hydrate gel is formed. When cement percentages were increased, the OMC of cement-treated samples was shown to increase in comparison to soil samples that were just treated with Nano-SiO_2. This can be explained by the heat of hydration that is released during mixing and compaction. Thus, it is possible to hypothesise that greater cement percentages release more heat during hydration, necessitating the use of greater amounts of water during mixing process (Kulkarni and Mandal 2022). When the percentage of nanoparticles increased for low Nano-SiO_2 concentration (up to 4%), the maximum dry density decreased at a slow rate. The fact that nanoparticles occupy the void inside the aggregate which can be used to explain the rise in maximum dry density of cemented sand mixed with Nano-SiO_2. With a rise in the Nano-SiO_2 content, the optimum water content of the cemented sandy soil sample increased. The behaviour can be accounted for by the fact that the nanoparticles offer a greater surface area that is prone to dehydration (Choobbasti and Kutanaei 2017). The OMC was marginally raised by adding Nano-SiO_2 to the clay and clayey sand. On the other hand, the maximum dry unit weight did not appear to vary significantly. The OMC in the sand was marginally decreased by the addition of Nano-SiO_2. There was just a slight variation in the maximum dry unit weight. In comparison to the specimens treated alone with cement, the maximum unit weight and optimal water content was increased when Nano-SiO_2 particles were introduced to the clay and clayey sand (Aksu and Eskisar 2023). As the Nano-SiO_2 content increased from 0.5 to 1% for a different percentage of lime dosage, the OMC increased and MDD decreased gradually; however, these tendencies were reversed at Nano-SiO_2 content of 1.2%. Agglomeration of the Nano-SiO_2 particles themselves may take place above the range of 1.1–1.2% Nano-SiO_2 additive, leading to the development of secondary CSH gel, which would raise OMC and subsequently lower MDD (Karimiazar et al. 2023). Because oil has a higher viscosity than water, it restricts the lubrication between soil particles. As a result, natural soil that has been contaminated with gas oil has shown reductions in MDD and OMC. Soil treated with Nano-SiO_2 pushed the compaction curve to the right, displaying a decrease in MDD and an increase in OMC. This alteration in the behaviour was attributed due to the nano-additive's larger specific surface area, which improved the water absorption and raised the OMC. The substitution of low specific gravity nanoparticles from natural soil was the cause of the decrease in MDD. A similar pattern of decreasing MDD and increasing OMC was also observed in the hydrated lime. The rise in OMC is caused by the high-water demand needed to fulfil the pozzolanic reactions that occur during the hydration process between the silica particles in the soil and calcium hydroxide. The development of more flocculated structures, which could hold larger volume and hence lower densities, was the cause of the decrease in MDD. When the additives are treated simultaneously, the MDD decreases and the OMC increases because the cation exchange reactions intensify since there are more silica particles available, which means that more water is needed to meet the hydroxyl demand during the interaction with the calcium ions (Nezhad et al. 2021). When Nano-SiO_2 was added to cement kiln dust (CKD) stabilized soil, it was found that the OMC and MDD of the treated soil were not significantly impacted. An increase in the amount of Nano-SiO_2 causes a modest decrease in MDD, which is explained by the agglomeration of nano-scaled powders, which increases the number of necks between particles and lowers the density of the corresponding framework (Ghavami et al. 2021). Using recycled polyester fibre and Nano-SiO_2, loess soil showed an increase in the OMC and a decrease in MDD (Sarli et al. 2020). The compaction parameters of sand with varying proportions of cement (5, 9, and 14%, by weight) and Nano-SiO_2 (5, 10, and 20%, by weight) showed that, at low cement content, an increase in the MDD of sand was observed with an increase in the dose of Nano-SiO_2 due to the filling effect that Nano-SiO_2 induces. On the other hand, because of the low specific gravity of Nano-SiO_2 relative to sand, there was a steady decline in the MDD seen following the nano-treatment of soil at high cement concentration. Furthermore, the larger specific surface area of Nano-SiO_2 led to an increase in the OMC of cement-stabilized sand (Choobbasti et al. 2015).

2.3.7 Effects of Nano-SiO_2 and Other Additives on Hydraulic Conductivity of Soil

The hydraulic conductivity is a crucial factor to take into account when constructing clay liners for structures that face seepage problems, such as water storage facilities, canal and tunnel linings, solid waste disposal sites, etc. The permeability properties of soil are influenced by a number of geotechnical parameters, including density, particle size, void ratio etc. The hydraulic conductivity increased as the concentration of both the 15 and 80 nm size nanoparticles with different percentages of cement content increased; nevertheless, the least conductivity was reported at 0.4% Nano-SiO_2. This indicates that adding Nano-SiO_2 to the soil reduced the amount of large pore spaces and removed the smaller ones, which may have been caused by the development of secondary C-S-H clusters. The 15 nm Nano-SiO_2 particles were more effective than the 80 nm nanoparticles in reducing the hydraulic conductivity. This could be because of the fact that 15 nm nanoparticles have a higher particle packing density than 80 nm nanoparticles. Nevertheless, more water was absorbed and retained by the soil and nanoparticles when the percentage of nanoparticles approached 0.8%, resulting in larger the hydraulic conductivity of the specimen (Bahmani et al. 2014). When the soil was treated with 3% white cement and 2% Nano-SiO_2, the highest reduction in permeability was attained. Similarly, permeability is reduced, and strength is therefore enhanced upon the addition of white cement and Nano-SiO_2. When soil is treated with both Nano-SiO_2 and white cement, the permeability decreases in the range of 0.00875 cm/sec, whereas when soil is treated with Nano-SiO_2 alone, the permeability drop is in the range of 0.01198 cm/sec. When compared to untreated soil, the permeability was reduced by about 45% for the treated soil. This behaviour demonstrates that white cement has a strong bonding capacity and a high permeability to Nano-SiO_2; the permeability of soil was decreased by combining these two stabilizing additives (Kulanthaivel et al. 2021). The hydraulic conductivity of the treated soil specimens at various curing ages and ratios of Sewage Sludge Ash (SSA) to cement, with or without 2% Nano-SiO_2, revealed that the hydraulic conductivity of the treated soil decreased with increasing curing time and that different ratios of the SSA to cement mixture decreased the hydraulic conductivity of the treated soil. Furthermore, specimens with a higher cement content or a lower SSA content at an early curing age had higher hydraulic conductivity when the SSA/cement ratio was taken into account. The addition of Nano-SiO_2 to the treated soil accelerates the calcium hydroxide reaction, leading to a slight rise in the hydraulic conductivity of the treated soil (Lin et al. 2016).

2.3.8 Effects of Nano-SiO_2 and Other Additives on Strength Characteristics of Soil

The compressive strength of soil composite significantly enhanced with the addition of Nano-SiO_2. Conversely, lesser silica nanoparticles loading resulted in higher strength. The highest strength for 4%, 6%, and 8% cement were 673 kPa, 1020 kPa, and 1611 kPa, respectively, when silica nanoparticles measuring 15 nm were used. The samples without Nano-SiO_2 had compressive strengths of 424 kPa, 450 kPa, and 515 kPa for cement concentrations of 4%, 6%, and 8%, respectively. The soil treated with 0.4% Nano-SiO_2 with 8% cement had a compressive strength that was 85% higher than the soil stabilized with 8% cement alone. Nevertheless, there was less strength gain was observed when a larger fraction of nanoparticle was added. Additionally, the test results showed that 15 nm nanoparticles were more successful than 80 nm nanoparticles in strengthening the soil. This could be because SiO_2 particles, which have an average size of 15 nm, have a larger specific surface area than the particles with an average size of 80 nm. Furthermore, at early stages of soil stabilization, it was found that the addition of smaller-sized nanoparticles increased the strength development rate at all the cement levels (Bahmani et al. 2014). With increasing curing age, the UCS values of samples treated with all grades of nano silica (NS-20, NS-30 and NS-40) and cement were found to increase. When compared to samples treated at lower doses, those treated with NS-40 showed greater strength. At 28 days of curing, the UCS values were found to be improved by 286.24%, 309.54%, and 348.15% upon the addition of 2%, 4%, and 6% cement. When compared to NS-30 and NS-40, the rate of strength development at 28 days of curing was found to be higher in NS-20 treated soil. It was also found to be higher than at 7 and 14 days of curing (Kulkarni and Mandal 2022). The UCS of samples for cemented sand shown a considerable improvement when the Nano-SiO_2 concentration reached an optimal level of 8%. However, as the Nano-SiO_2 content grew from 8% to 12%, the UCS declined. The enhanced UCS of the cemented sand sample containing Nano-SiO_2 is due to the rapid consumption of calcium hydroxide (CH) by the highly reactive Nano-SiO_2 particles during the hydration process of the cement agent (Choobbasti and Kutanaei 2017). When clean and contaminated soil specimens were treated with a Nano-SiO_2-lime combination, the UCS of the sample increased considerably. The results show that this significant improvement was caused by an increase in both the stabilizing additives and the curing time. The addition of Nano-SiO_2 and lime suggests that a pozzolanic material with a high SSA when exposed to lime, it accelerates the pozzolanic reaction until the material is available (Nezhad et al. 2021). After 28 days of curing, soil with 1.0 or 1.2% Nano-SiO_2 and 6 or 8% lime showed significant increases in compressive strength values, reaching around 1400 kPa for the lime-stabilized specimens with Nano-SiO_2. The enhanced strength mobilized for the stabilized soil test specimens could be partially ascribed to the partial carbonation of lime, which also had a strengthening effect. The formation of secondary CSH in chemical interactions with Nano-SiO_2 may have been triggered by the calcium species in lime, as indicated by the time-dependent, progressive increase in the compressive strength results. The formation of these CSH phases, bind the soil particles together and improved the test specimen's overall strength (Karimiazar et al. 2023). With the addition of 1.0% NS, the UCS of cement-solidified dredged sludge (CDS) was significantly higher than it was without NS. Additionally, it was noted that the 60-days UCS of CDS with 1.0% NS was more than twice as high as that without NS, and that the 60-days UCS of CDS was much greater than the 28-day UCS when 1.0% NS was added. The considerable improvement in the UCS was caused by the additional CSH formed in the CDS as a result of the interaction between SiO_2 and $Ca(OH)_2$. The inclusion of NS resulted in several mechanical and physical advantages, such as an increase in cohesion between the soil particles and an improvement in the compactness. Additionally, cement hydration and the inclusion of NS help CDS to develop its long-term strength. The consumption of $Ca(OH)_2$ by NS developed the secondary hydration reaction with the advancement of cement hydration, resulting in a notable improvement in subsequent strength. Additionally, the degree of cement hydration has an impact on how much NS contributes to the development of CDS strength (Lang et al. 2020).

2.3.9 Microstructural Characterization of Soil Stabilized with Nano-SiO_2 and Other Additives

The SEM analysis of three specimens such as an untreated specimen, a specimen treated with 8% cement, and a specimen treated with 8% cement and 0.4% SiO_2 nanoparticles showed that the untreated soil was composed of certain particle packs.

This might be because clay particles stick to each other when water is present, forming large particle packs that resulted in a high micropore count in the untreated soil. A denser soil matrix was produced in cement-treated soil by particle packs with smaller pores because some of the pore spaces were filled with cementitious gel. The cement-treated soil micrograph containing Nano-SiO_2 showed the formation of an extremely dense matrix and extensive pore filling. It might be a reflection of the reactions between the SiO_2 nanoparticles and cement products that lead to the development of secondary C-S-H gel. The soil is strengthened, and the soil particles are enveloped by these reaction products. Furthermore, SiO_2 particle nano-filling may raise the soil's packing density. Moreover, a better dispersion of C-S-H gel in the matrix could be facilitated by the nucleation action of the particles (Bahmani et al. 2014). According to XRD analysis, adding Nano-SiO_2 particles to the cement treated soil causes the intensity of the CH peaks to decrease and the CSH peaks to increase. However, the sample containing 12% more Nano-SiO_2 than the required amount inhibits the formation of CH crystals, which lowers the ratio of CH crystals to CSH gel. No hydration response would happen if CH crystal formation was inappropriate. As a result, the sample develops micro cracks and the UCS drops. Similarly, the SEM data show that a compact microstructure is developed when nanoparticles are added to a cement-treated sand mixture. The reduced quantity of CH crystals further suggests that the addition of nanoparticles, up to the optimum percentage, facilitates the hydration process, particularly in the early stages of curing, and converts all of these dehydrated crystal needles into CSH gel. Furthermore, there are unstable lumps in the microstructure of the sample containing 12% Nano-SiO_2. The cement treated sand sample is more susceptible to standing unconfined compressive loads because of these unstable lumps than samples with lower Nano-SiO_2 contents (Choobbasti and

Kutanaei 2017). The microstructural properties of the cement and Nano-SiO_2 treated soils obtained from SEM analysis revealed the existence of needle shaped ettringite, sheet like or cloudy CSH, and some hexagonal shaped CH in the 7-day soil specimens. These are explained by the addition of Nano-SiO_2, which facilitates the microscale cement hydration process and influences the characteristics of the soil (Aksu and Eskisar 2023). The results of the XRD analysis performed on 28-day-cured sample of the soil treated with 6 % lime, soil treated with 1 % Nano-SiO_2, and soil treated with 6 % lime and 1 % Nano-SiO_2 combinations, as well as for the untreated soil, showed that both the additives were effective in generating Ca $(OH)_2$, which helps to form secondary CSH. The addition of lime resulted in the creation of CH peaks, some of which were associated with ettringite (ET) formation. The CH related peaks in the soil treated with 6% lime were greater than those in the soil mixed with Nano-SiO_2 addition. The addition of Nano-SiO_2 to the soil treated with 6% lime changed the strength of the CH peak and eliminated the peaks associated with the ET compound. Since these nanoparticles have larger SSA and inhibit the production of ET, a rise in the CSH peak strength with increasing Nano-SiO_2 content may be expected to correlate with a higher pozzolanic Nano-SiO_2 response at later stages. The XRD data indicate that CSH was produced more successfully in the sulfate-bearing lime-treated marl soil sample with 1% Nano-SiO_2 than in the 6% lime-treated soil sample. In addition, it may be concluded that the addition of Nano-SiO_2 may have had the dual impact of enhancing the intensity of CSH through the nucleation effect and hydration acceleration (Karimiazar et al. 2023). The SEM micrographs of solidified dredged sludge (DS) with cement, lime, and NS at 28 days showed that the quantity of cementitious products grew and the cementation bond between the cementitious products and the DS particles strengthened as the cement concentration increased. The hydration products CSH and CAH filled the pores between the DS particles after 28 days of curing, indicating that they are the primary hydration products of cement. By adding NS, cement hydration was accelerated and more CSH was generated. Furthermore, the quantity of CSH and the compactness of the microstructure increased with the rise in NS concentration. The primary mineralogical components of DS were identified by the XRD examinations of cement-solidified dredged sludge (CDS) samples conducted at 28 days. These tests revealed the presence of quartz (Q), kaolinite (K), berlinite (B), and illite (I) in all examined CDS samples. Additionally, all the analysed samples contained the hydration products CSH and CAH, indicating that they were the primary hydration products of cement. Only the solidified dredged sludge with 15% cement exhibited Ca $(OH)_2$, while the other CDS samples showed no evidence of it. This was ascribed by the secondary hydration reaction that the NS addition induced (Lang et al. 2020).

2.3.10 Effects of Nano-SiO_2 and Other Additives on Durability Characteristics of Soil

The prevention of strength degradation due to thermal cycles is significantly impacted by the combination of glass fibre and Nano-SiO_2. Thermal cycles do not generally impact the strength reduction caused by the variation in the glass fibre and Nano-SiO_2 contents. After 12 thermal cycles, the strength reduction ranged from 22% to 33% for all samples with different additive mixes. In fact, the strength reduction is about the same for all glass fibre and Nano-SiO_2 combinations. In other words, after 12 thermal cycles, the results for the peak strength decrease for different combinations of additives were rather close to each other. After putting the samples through 12 thermal cycles, it can be said that the variation in the glass fibre and Nano-SiO_2 contents did not significantly affect the ability to stop the samples compressive strength from decreasing. Furthermore, it was shown that as the number of thermal cycles increased, the discrepancies between two successive peak strengths decreased. The combination of 1.0% Nano-SiO_2 and 2.5% glass fibre yields a higher shear strength; however, due to thermal cycles, the same additive concentrations also resulted in the largest loss in shear strength. The addition of Nano-SiO_2 and glass fibre increased the contact surface area of clay particles, which resulted in a reduction of the internal friction angle of the treated clay that was less than that of the natural clay after 12 F-T cycles (Ahmadi et al. 2021). The inclusion of cement and soil treated with Nano-SiO_2 typically exhibited a degree of resistance against the freezing-thawing-induced loss of strength in the specimens. The most durable specimen after twelve cycles of freeze-thaw was clayey sand with 10% cement and 0.5% Nano-SiO_2, which lost just 8% of its strength. The porosity and size of the soil particles, as well as the quantity of cement, Nano-SiO_2, and water, all influenced the energy absorption in the specimens. The specimen's interior porosity and microcracks gradually increased with each application of the freeze-thaw cycle. The specimens subjected to F-T cycles absorbed comparatively less energy than those were not subjected to such cycles. When clay with 5% cement and 0.5% Nano-SiO_2 was used, the amount of absorbed energy was lowest. By applying freeze-thaw cycles continuously reduced the absorbed energy, which in turn lowered the peak strength and the associated strain level (Aksu and Eskisar 2023). Based on the results of tests carried out before to the F-T cycles, the samples those were stabilized with 0.5%, 1%, 1.5%, and 2% of Nano-SiO_2 and 7% of lime content were prepared for testing after undergoing consecutive freezing and thawing cycles. The strength of the specimen declined, and their behaviour becomes less brittle as a result of an increase in F-T cycles because the cohesion and interlocking among the soil particles are reduced. After the completion of the ninth F-

T cycle, the specimens containing the optimal percentages of Nano-SiO_2 1.5% and lime 7% experienced a reduction in their maximum shear modulus and compressive strength of 17% and 54%, respectively. Notably, this decreasing trend was less pronounced than that of the other samples containing different amounts of additives. After nine F-T cycles, the strength of the samples without Nano-SiO_2 was reduced by roughly 64% (Jafari and Lajevardi 2022). As Portland cement (PC) concentration increased, the cement-solidified dredged sludge (CDS)'s water absorption (WA) decreased because of the cementitious compounds that resulted from PC hydration. The internal pores were filled by the cementitious materials produced by PC hydration, which enhanced CDS's imperviousness. The WA dropped when fly ash was added to CDS, but it grew as fly ash content increased. For decreasing WA of CDS, Nano-SiO_2 was more successful than fly ash. In comparison to 15% PC alone, using 15% PC with 0.9% Nano-SiO_2 for solidifying dredged sludge can significantly lower 7-day WA by 40% (Lang et al. 2020). Three different types of specimens such as untreated bentonite, bentonite with 0.5% Nano-SiO_2, and another mixture of bentonite, 15% Electric Arc Furnace (EAF) slag, 0.5% Nano-SiO_2 were exposed to freeze-thaw cycles, with curing time of 7 and 28 days. After 7 and 28 days of curing, the bentonite treated with EAF slag indicated a decrease in the UCS value of 21% and 7.4%, respectively, following freeze-thaw cycles. The samples that were cured for 7 and 28 days and treated with Nano-SiO_2 alone had strength loss rates of 31% and 16.4%, respectively, which were roughly 1.4 and 2.6 times lower than the untreated samples. The strength of the sample that was treated with Nano-SiO_2 and EAF slag and then cured for 28 days following four cycles of freezing and thawing, was 3.9 times greater than the strength of the untreated sample. This indicates that the curing time significantly improved the treated samples' performance against the cycles. After

4 cycles of freezing and thawing, the strength of the sample that was cured for 7 days using both the stabilizers was 1.1 times greater than the sample that was cured for 28 days using only Nano-SiO_2 (Shahsavani et al. 2021).

2.4 DYNAMIC CHARACTERIZATION STUDIES OF SOIL STABILIZED WITH FLY ASH

The shear modulus (G) and damping ratio (D) are the dynamic parameters of the soil that are needed to analyse the dynamic problems including vibration amplitude, foundation resonance, and seismic analysis. Many studies have been done on dynamic characterization of clayey soil stabilized with flay ash (Saride and Dutta 2016; Lang et al 2020; Petcherdchoo et al. 2023). The fly ash treated specimens were subjected to confining pressures of 25, 100, and 200 kPa for 28 days. The normalized shear modulus reduction G/G_{max} curves of the specimens showed that the value of G/G_{max} decreased from 1 to 0.1 when the shear strain increased from 10^{-4} to 10^{-1}%, respectively. This can be attributed to the treated specimen's strong stiffness against shear at low strain range. At greater shear strain levels, however, particle-particle slippage and the breaking of pozzolanic connections will occur, which will result in a considerable deterioration of the shear modulus. The specimens treated with a high dosage of stabilizer exhibit stronger initial shear stiffness, which may account for the deterioration of the shear stiffness at higher fly ash dosages. The pozzolanic interaction between fly ash and soil cause the cementation of fly ash at the particle-to-particle interfaces of clayey soil. As a result, the treated specimen becomes more rigid, increasing its shear stiffness (Saride and Dutta 2016). The variation of shear modulus (G) with changes in shearing strain was examined in relation to the effects of varying percentages of cement and fly-treated silty clay subjected to confining pressures of 50, 100, and 200 kPa with curing age. It was noticed that the G increased as the confining pressure increased. This is because the voids between the soil particles were compressed by an increase in confining pressure, which led to an increase in sample compactness. The rise in G can be attributed to the higher compactness. It was evident that the G dropped nonlinearly with shear strain when the torsional vibration in the sample caused its internal structure to loosen until it was destroyed. The G of the cement-fly ash-stabilized silty clay (CFSC) with 5% cement and 30% fly ash was greater than that of cement stabilized silty clay with 15% cement. This suggests that improving the G can be achieved more successfully by stabilizing silty clay with 5% cement mixed with 30% fly ash rather than 15% cement alone. The process of cement hydration stabilized the cemented soil by generating calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH), which strengthen the bond between the soil particles. Moreover, the long-term strength development is due to the production of additional CSH and CAH from the secondary hydration reaction between clay minerals (mostly SiO_2 and Al_2O_3) and Portlandite (Ca $(OH)_2$). The filling effect of fly ash for CFSC also enhanced the compactness, which raised the G. Thus, there are more benefits of using cement in combination with fly ash as a stabilizer to increase the G of silty clay than that of the utilization of cement alone. As the curing age grew, the G also increased. With longer curing ages, there was more cement hydration and the creation of hydration products (CSH and CAH) (Lang et al. 2020) which helps in the strength improvement of the treated soil.

2.5 DYNAMIC CHARACTERIZATION STUDIES OF SOIL STABILIZED WITH NANO-SiO_2 AND OTHER ADDITIVES

The clay soil treated with 1% cement and optimal doses of both boienzyme and Nano-SiO_2 showed a decrease in shear modulus value with increasing cyclic shear strain amplitude. During the first few loading cycles, the shear modulus decreased dramatically; however, it thereafter declined steadily. The treatment effect was more pronounced at lower strain levels up to 1.575%; after that, there was no discernible increase in the shear modulus. The cyclic stress that develops for cyclic shear strains of 0.45 and 0.75% may be able to disrupt the bridge network between the consolidated clay particles in both treated and untreated soils; this could be the cause of the fall in G value that occurs as the number of cycles increases. However, in the case of cyclic shear strain more than 2.25%, the soil may be going through stress conditions that cause the particles to reorganize themselves in an elastic form, thereby halting the breakdown of the particle-particle force network. An increase in cyclic shear strain results in an increase in the damping ratio of the soil matrix. The stabilized soil exhibited a 1.7 times larger damping ratio than the untreated soil, which could have a major impact on the soil's response to seismic activity (Thomas and Rangaswamy 2020). The measured shear wave velocity and small strain shear modulus for the samples containing 1% Nano-SiO_2 exhibit a significant increase upon increasing the lime content from 5 to 7%. Nevertheless, there is no discernible difference in the variation of the shear wave velocity when the lime concentration is increased from 7 to 10%. Consequently, the optimum percentage for the samples containing 1% Nano-SiO_2 can be considered to be 7% lime content (Jafari et al. 2021). The effects of the 28- and 56-days curing period on the (G_{max}) of the clay samples stabilized with cement and Nano-SiO_2 showed that an increase in the curing duration was shown to produce an increase in (G_{max}) for all specimens with different cement and Nano-SiO_2 concentrations. Additionally, the samples that were cured for 28 and 56 days showed nearly identical patterns in the rise in (G_{max}) of the stabilized soils with the addition of Nano-SiO_2. It is notable that, for both the curing period, the samples with different cement amounts show nearly constant (G_{max}) or even slightly decreasing values beyond around 0.5% Nano-SiO_2 content. Thus, it can be generally stated that at different cement percentages, roughly 0.5% is the most optimal and cost-effective level of Nano-SiO_2 content in terms of improved stiffness (Heidarizadeh et al. 2021). The addition of different percentages of fly ash and 1% Nano-SiO_2 at different confining pressures and curing duration resulted in an increase in the specimen's low-strain shear modulus (G_{max}) (Munda et al. 2023). The inclusion of Nano-SiO_2 effectively lowers the cement soil's cumulative plastic axial strain and raises its dynamic elastic modulus. The cumulative plastic axial strain and dynamic elastic modulus modification effect coefficients for the specimen containing 0.4% Nano-SiO_2 are 0.481 and 0.698, respectively. This suggests that the addition of Nano-SiO_2 at the optimal content resulted in a nearly 50% reduction in the last cumulative plastic axial strain and a nearly 70% increase in the last dynamic elastic modulus when compared to the specimen without Nano-SiO_2 (Wei et al. 2024). There is very limited study on the dynamic characterization of clayey soil stabilized with Nano-SiO_2 and other additives. Hence, further study is required to investigate the performance of the clayey soil stabilized with Nano-SiO_2 and other additives under dynamic loading condition.

2.6 CHALLENGES IN THE FIELD APPLICATION OF NANO MATERIAL FOR SOIL STABILIZATION

Although nanotechnology in the field of civil engineering have many potential uses and applications, it is crucial to maintain perspective and recognize the difficulties and constraints that this subject currently facing. This section provides a brief overview of the obstacles and restrictions that may have an impact on certain applications. The challenges and worries include those related to health, safety, and the environment, as well as cost issues when using nanoparticles in various applications. The safety of nanomaterials for both the environment and people is a source of worry when using them in the field applications. Road pavement is a specific area where these problems need to be addressed because people live adjacent to road and travel on these surfaces, where they may come into direct touch with nanomaterials without realizing it. The engineer's goal is to find practical solutions to real-world issues and build facilities that the general public can use at a fair price. The development of new composite material and the improvement of soil properties are two benefits of using nanomaterials in geotechnical engineering. Some of the challenges during field applications are discussed below:

2.6.1 Effects on Environment

Research on nanotechnology and the environment is focused on the impact of different nanomaterials on the environment. Various enquiries have been prompted by uncertainty about the possible consequences of materials that exist on the nanoscale yet have attributes distinct from those when using the material on a micro- or macroscale (Karn et al. 2003). Significant amounts of nanoparticles are unavoidably released into the environment as a result of the growing production and use of nanomaterials. Fig. 2.1 illustrates a diagram representing the release of nanoparticles in the environment. Through various gas-to-particle conversion techniques, nanoparticles can be directly generated from gases and released into the environment (Friedlander and Pui 2003). The main cause of nanoparticle contamination in rivers, lakes, and aquatic fields is the discharge of industrial waste containing nanoparticles (Daughton 2004). In certain places, nanoparticles make up the majority of the ambient air particles. Their extremely small size and high surface area to mass fraction play a significant role in the atmospheric chemistry of these particles and the associated health risks to the environment. Since pavements are developed in natural environments, all materials used in their construction and maintenance, including nanomaterials, must be compatible with nature and should have minimal adverse effects on it. The typical possible issues here are materials seeping into groundwater, dust from unpaved roads releasing pollutants into the air, and workers being exposed to potentially hazardous compounds when doing maintenance and construction work. However, the usage of nanomaterials is frequently motivated by their unique properties both at the nanoscale, where they behave differently, and at the nanoscale, where they have different environmental effects (Steyn 2009).

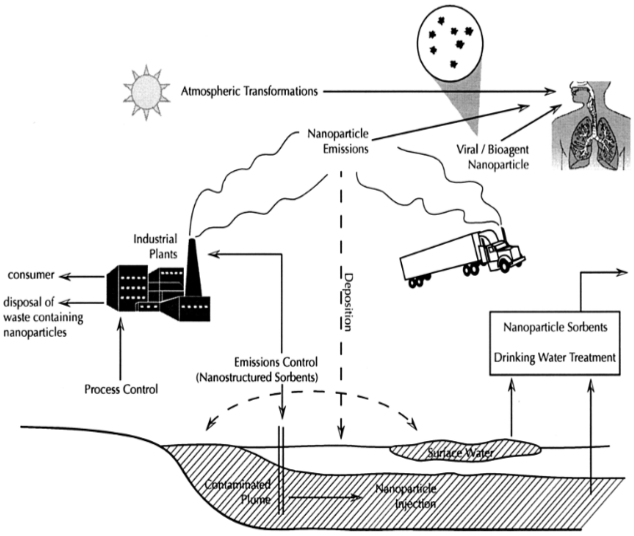

Fig. 2.1. Schematic diagram illustrating nanoparticles in the environment (Biswas and Wu 2005).

2.6.2 Effects on Health and Safety

The possibility for exposure and the hazard that nanoparticles pose to human health determine the health risk associated with them. It is advisable for users of nanoparticles to try to reduce any possible dangers as early in the design process as possible, rather than waiting until after manufacturing or customer use. According to the past studies on the biological impacts of nanoparticles, engineered nanomaterials are unexpectedly hazardous to living organisms and have negative consequences on human health (Kreyling et al. 2006; Simkó and Mattss 2010). Fig. 2.2 depicts the human body with health effects of nanoparticles. It is important to note that not all nanoparticles have these harmful effects on health; rather, the toxicity of a given nanoparticle relies on a number of parameters, such as its size, composition, aggregatetion, crystallinity, surface functionalisation, etc. Nanoparticles that penetrate the bloodstream are associated with heart problems, arteriosclerosis, blood clots, arrhythmias, and ultimately cardiac death. Translocation of diseases affecting these organs to other organs like the liver, spleen, etc., can also occur. Exposure to specific nanoparticles has been associated with autoimmune illnesses, including rheumatoid arthritis, scleroderma, and systemic lupus erythematosus (Buzea et al. 2007). It was discovered that crystalline silica was more hazardous than amorphous or colloidal silica particles when the pulmonary responses of rats to the two types of silica were examined (Warheit et al. 1995).

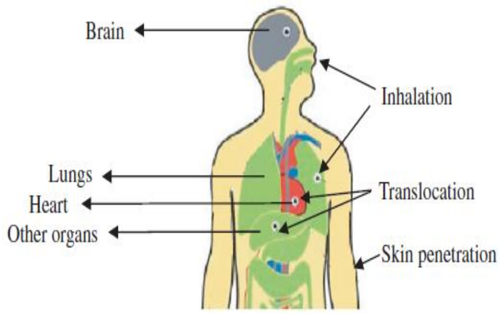

Fig. 2.2. Schematics of human body with health effects of nanoparticles (Buzea et al. 2007).

2.6.3 Costs

Now a days, the majority of materials and equipment used in nanotechnology are rather expensive. This is caused by both the complexity of the apparatus and the novelty of the technology. On the other hand, the costs of nanomaterials have been established to decline with time, and it is anticipated that these costs will continue to decline as manufacturing technologies are developed. In the near future, the cost of manufacturing Nano-SiO_2 will come down due to the positive uses in the biotechnology and construction industries, as well as the encouraging advancements in biogenic production methods. The most economical approaches to solving the field application problems can still be the conventional methods by using cement and lime. The purpose of this research is to achieve the potential of nanomaterials to substitute conventional materials in civil engineering to optimise the cost of the construction projects, i.e., to lower project costs and contribute to a reduction in global warming by using less amount of cement and lime.

2.7 SUMMARY

The concise summary regarding the stabilization of problematic soil using fly ash and nanoparticles with various additives has been discussed in this section. Over the past century, a large number of multidisciplinary studies on nanoscale materials and technologies have been reported; these studies include both comprehensive scientific study and potential applications. This area of study has developed into one of the most important for the advancement of modern technology. Past studies suggest that silica nanoparticles can be used to improve the strength characteristics of soil. Strength enhancement of soil occurs through the creation of viscous gels and void filling in the soil matrix treated with Nano-SiO_2. The geotechnical characteristics of soil can be significantly enhanced by adding nano additives alone, but the engineering properties of soil can be further modified by adding pozzolanic materials like cement and lime, which have comparable effects. The homogeneous dispersion of pozzolanic materials in the soil structure was enhanced by the nano additives, leading to an improvement in the reactivity at both the nano- and micro-scale. Because of their greater reactivity, the nano-additives are applied to reduce the consumption of pozzolanic materials.

Nanotechnology might be the key to a completely new world in the domains of geotechnical engineering. Although it is not possible to replicate natural systems, materials at the nanoscale can be used to build infrastructure, and there are a number of promising developments that may alter the life-cycle costs and service life of infrastructure to create new worlds in the future. Based on the information provided and the arguments made in the previous study report has been discussed briefly in this chapter and summarized as follows:

- The researchers started by examining the fundamental characteristics of fly ash and identifying various types of problematic soil. Subsequently, the problematic soil was stabilized using the industrial waste such as fly ash. The addition of fly ash to the soil resulted in a decrease in MDD and an increase in OMC. This may be due to the lower specific gravity of the fly ash.
- As the fly ash content increased, the CH soil's plastic limit and liquid limit increased while its plasticity index declined. The liquid and plastic limits are raised by the aggregation of clay particles and flocculation, which increases the soil's ability to retain water.
- The addition of fly ash raised the soil's UCS and CBR values; nevertheless, class C fly ash is more efficient than class F fly ash. Because fly ash possesses time-dependent pozzolanic capabilities, an increase of the curing period improves the UCS of soil. Fly ash stabilization involves pozzolanic reaction and cation exchange. On the other hand, pozzolanic reaction influence is greater than cation exchange influence.
- Nanoparticles aggressively interact with the other particles because of their large specific surface area and ability for cation exchange. The strength characteristics and microstructure of the soils can be enhanced with the application of these substances.
- With the addition of nano-additives, the majority of fine-grained soils, including silty clays and clays with low, intermediate, and high compressibility, showed a decrease in MDD and an increase in OMC. The lower specific gravity of the nano-additives compared to soil particles was the reason for the decrease in MDD,

whereas the availability of more water absorption sites was the cause of the greater OMC.

- Some researchers have reported that the normalised modulus degradation ratio (G/G_{max}) dropped as the dosage of fly ash increased. The damping ratio (D) drops as the fly content and confining pressure rise. The soil becomes more rigid and particle slippage and rearrangement significantly decrease when the confining pressure and cementation level rise, which lowers the soil's damping ratio.
- Few researchers have reported on the dynamic characteristics of problematic soil using silica nanoparticles.

From the above discussion, it can be concluded that, Nanoscience and technology are considered to be the most significant scientific and technological fields of the twenty-first century because of their capacity to alter the traditional construction materials and contribute to the advancement of sustainable development. The application of nanotechnology in the construction engineering has improved the fundamental characteristics of materials. Nanomaterials have the potential to improve safety, minimize the cost of civil infrastructure, and lessen the energy and environmental impact of construction industry. Several laboratory-based studies have shown that only a very tiny fraction of silica nanoparticles significantly alter the properties of soil due to their increased specific surface area and strong reactivity. Previous research indicates that due to its versatility and performance in a range of applications, Nano-SiO_2 is one of the most extensively used nanoparticles for stabilizing soil when compared to other nanoparticles. Although many investigations have been carried out on the static strength behaviour of soil that has been treated with Nano-SiO_2, minimal research has been done and is available on its dynamic behaviour. The research on the G/G_{max} and damping characteristics of clay soil treated with Nano-SiO_2 and fly ash is relatively scarce. In addition, researchers are searching for innovative waste-based binders to partially or completely replace conventional binders owing to the substantial CO_2 gas emissions and consumption during the production process. The utilization of Nano-SiO_2 and fly ash-treated clayey soils in various civil engineering applications particularly for flexible pavement application contributes towards sustainable development and a reduced carbon footprint. Hence, further study is required to investigate the strength performance of the clayey soil stabilized with Nano-SiO_2 and other additives under dynamic loading condition. Here, the primarily focus of the study is to explore the potential of the clayey soil treated with Nano-SiO_2 and fly ash for a broad range of geotechnical applications.