CHAPTER- I

INTRODUCTION

1.1 GENERAL BACKGROUND

The growing global population and constrained space in the urban areas are forcing civil infrastructure to expand into the unfavourable ground conditions. As a result, there is an increasing requirement for ground development projects to make space for the civil infrastructure expansions. Soils beneath a structure, whether commercial or residential, should be able to support the weight without experiencing any short- or long-term settlement or shear failures. Soft/weak soils are more prone to failures due to these two factors. Various techniques, including mechanical, chemical, and biological stabilisation, have been used to modify the geotechnical characteristics of weak and soft soils in accordance with field requirements (Behnood 2018; Renjith et al. 2020; Sidiq et al. 2023; Little and Nair 2009). An economical and widely used technique in geotechnical engineering to enhance the properties of soil and to increase its suitability as a construction material is soil stabilization (Firoozi et al. 2017). Conventional calcium-based soil additives, such as cement and lime are regularly added to the soil to enhance the effectiveness of soil stabilization (Asgari et al. 2015). Although the majority of applications have demonstrated the effectiveness of calcium-based additives, their main drawback has been extensively studied in the past and has primarily been related to the environmental impact associated with their production. For example, the cement industry is the second largest industrial contributor to CO_2 emissions worldwide, contributing 7% of CO_2 emissions from the production of

Portland cement, a popular soil stabilizing agent (WBCSD 2018). The effects of lime production on the environment might be local, regional, or global level. The mining of limestone has localized effects such as dust emissions and altered landscapes. Acid rain is a regional issue caused by sulphur dioxide and nitrogen oxide emissions, while global climate change is caused by carbon dioxide emissions (Gutiérrez et al. 2012). Because of these reasons, a lot of research have been done in order to develop a novel types of sustainable stabilizing binder with the goal of reducing the environmental impact that comes with utilizing cement and lime as a stabilizing agent.

1.1.1 Scenario of Problematic Soil

All around the world, soils are a vastly diverse range of nonhomogeneous and anisotropic natural materials. Despite having adequate geotechnical properties, some soils might not be suitable for use in geotechnical engineering applications. Some soils are referred to as problematic soils in various regions of the world because they are challenging to work with both during and after foundation construction. Fig. 1.1 depicts the major soil map of India. The physical and mechanical characteristics of several Indian soil types provide major issues in the field of geotechnical engineering. The problematic soil types that are frequently found are listed below.

1.1.1.1 The major problematic types of soils found in India

Laterite Soil: The country's laterite soil is found mostly along the coasts in the areas that experience considerable rainfall interspersed with periods of alternating drought and precipitation. They are reddish-pink in colour due to the iron oxide that they contain, which is formed during the breakdown of rocks. This kind of acidic soil typically has low levels of lime content and a nitrogen deficiency. The Western and Eastern Ghats, Vindhyas, Malwa Plateau, and Satpuras are the primary locations where it may be found throughout the nation. This kind of soil can be found in a number of states, including West Bengal, Andhra Pradesh, Bihar, Meghalaya, Assam, and Odisha. The challenges involved in laterite soil are significant variations in soil strength, challenges in excavating, and likelihood of excessive wear on construction machinery.

Black Soil: Lava and volcanic rocks comprise this type of soil. Since cotton is a significant crop that is grown in black soil, the soil type is sometimes referred to as black cotton soil. Although the amount of phosphorus in this soil is low, it is rich in calcium carbonate, potash, lime, and magnesium carbonate. Furthermore, it can be found in various states, including Tamil Nadu, Andhra Pradesh, and Karnataka. It is clayey and very good at retaining moisture. When it's dry, it cracks and gets sticky during the wet season. The challenges involved in black soil are poor load-bearing capacity, high shrink-swell capacity, and severe cracking potential.

Red Soil: The weathering of igneous and metamorphic rocks produces this kind of soil. The soil's high iron content is what gives it its red colour. Though mostly loamy, the soil's texture can range from sandy to clayey. It has a high potash content but low levels of phosphate, humus, and nitrogen. The areas with red soil include Tamil Nadu, Madhya Pradesh, Jharkhand, Odisha, southeast Maharashtra, and certain areas of Karnataka. The challenges involved in red soil are poor load-bearing capacity, high compressibility and risk of erosion.

Alluvial Soil: The deposits of sediments carried by rivers create alluvial soils. The majority of rivers have their source in the Himalayas and carry a significant amount of silt with them. The particles like silt, sand, and clay make up the soil. It contains lime, potash, and phosphoric acid in sufficient amounts. With its 40% land coverage, it is the most significant type of soil in the nation. It covered in the northern plains, which stretch from West Bengal and Assam to Punjab. In peninsular India, it can also be found in the deltas of several rivers, including the Krishna, Godavari, Kaveri, and Mahanadi. The challenges involved in alluvial soils are high compressibility, low shear strength, challenging to achieve proper compaction because of the varying composition and moisture content, and risk to erosion.

Desert Soil: The areas with little precipitation and arid or semi-arid climates are home to desert soil. Partially blown from the Indus Valley, and partially indigenous, is the sand found in the desert regions. There are 90–95% sand particles and 5–10% clay particles in this soil. Low levels of nitrogen and high levels of phosphates are present in this soil**.** The majority of Rajasthan, stretching to the Rann of Kutch, as well as certain parts of Haryana and Punjab, have desert soil. The challenges involved in desert soil are low moisture content that can lead to inadequate compaction, an excessive amount of dust, and an increased risk of erosion.

Saline and Alkaline Soil: The earth is filled with a variety of inert mineral materials. As a result of weathering, they emit salts of calcium, magnesium, sodium, and sulphurous acid. Some areas of Gujarat, Punjab, and Uttar Pradesh have this kind of soils. Soil salinization happens in the coastal areas as a result of salt build up from flooded seawater. The challenges involved in saline and alkaline soil are potential for decreased load-bearing capability and corrosion of the foundation and building materials.

Peat Soil: Peat soils are generated when a high amount of organic matter builds up in the soil in humid areas. These kinds of soils have a fair amount of soluble salts and between 10 and 40 percent organic content. Soils that are rich in peat are dense, dark, and highly acidic. Certain districts of Kerala have soils that are marshy or peaty. Conversely, coastal regions of several states, including Tamil Nadu, Bihar, Uttaranchal's Almora district, and West Bengal's Sundarbans, have marshy soils. The challenges involved in peat soil are excessive settlement over time, excessive compressibility, and low load-bearing ability. On these soils, deep pilings or other specialized methods are frequently needed for foundations.

Mountain Soils: Mountain soils are often shallow, in-depth, and immature because they are generated by the build-up of the organic matter that comes from the forest development. Sand and gravel are typically present. The Eastern Ghats, Peninsular India, Arunachal Pradesh, Assam, and the Himalayan region are the primary locations for it. The challenges involved in mountain soils are erosion and stability issues, variable soil composition and rock fractures.

Fig. 1.1. Major soil map of India (Maps of India, 2022)

In order to deal with these problematic soils and ensure their suitability, engineers commonly employ a range of mitigation strategies, including as ground improvement techniques, soil stabilization, and cautious foundation design.

1.1.2 Scenario of Industrial Waste

The solid residue left over after burning coal in the thermal power plants is called coal fly ash (CFA). In contrast to typical industrial by-products, CFA is a complex anthropogenic material that is hazardous and difficult to handle. Its complex composition, which includes both organic and inorganic compounds at varying sizes obtained from different grades of coal, is the cause of its toxicity. Furthermore, the use of coal-based energy has increased, producing enormous amounts of CFA, due to the cheap availability and inexpensive cost of coal, rising global energy demand, and obvious unreliability of alternative energy sources. Several millions of tonnes of ash and associated byproducts have been produced since the 1920s, when large-scale coal combustion for electricity production was started. It was reported that 600 million tonnes of coal ash was produced annually worldwide, of which 500 million tonnes, or 75–80% of the total, were fly ash (Joshi and Lohita 1997). As a result, fly ash is being emitted in greater quantities by manufacturers and thermal power plants worldwide, and disposing of this vast volume of fly ash is becoming a major environmental issue (Joshi and Lohita 1997). Fly ash particles are evaluated as highly polluting due to their enrichment in potentially harmful trace elements that condense from the flue gas. Research on potential uses for these wastes is important for the environment in addition to being of utility to industry. The majority of fly ash produced is dumped in landfills, a practice that is being investigated for potential environmental risks (Ahmaruzzaman 2010). Beginning in the early 1980s, the idea of sustainable development was introduced in an effort to bridge the gap between socio-political concerns about human development issues and the environmental concerns about the increasingly evident ecological consequences of human activities (Robinson 2003). Ever since the concept of sustainable development gained popularity. Researchers and industry professionals have endeavoured to find methods for enhancing the sustainability of industrial processes (Brundtland 1987). The use of fly ash as an additive to improve soil properties results in decreased or eliminated waste storage costs as well as less negative environmental effects, in addition to increasing soil strength properties. The thickness of road pavement reduces with the improved soil strength, which saves a lot of money on the construction of the road (Sengul et al. 2023).

A significant source of electricity in many nations across the world are thermal power plants that run on coal. More than 100 million tonnes of coal are produced annually in the top ten nations, which include China, India, South Africa, Germany, Poland, the United States, Indonesia, Russia, Australia, and Kazakhstan. According to the BP Energy Outlook 2018, China was the world's biggest coal user in 2015. India's coal consumption for various coal-based thermal power plants may double from 407 to 833 million tons oil equivalent (mtoe) between 2015 and 2035 (BP Energy Outlook 2018). From 2015 to 2035, the United States' coal demand is expected to decline significantly, from 396 to 198 mtoe (BP Energy Outlook 2018). The production and use of coal fly ash (CFA) worldwide is shown in Fig. 1.2. The countries using coal fly ash at 100% include Denmark, Italy, and the Netherlands; Japan uses it at 96.3%, France uses it at 85%, and Canada uses it at 75%. The usage rate in India is only 38%. Approximately 40% of all energy produced worldwide is derived from coal, according to a 2014 assessment by the US Energy Information Administration (USEIA). This percentage is expected to rise rapidly as more thermal power plants are built in major coal-producing countries like China and India. Due to the huge use of coal to meet the world's expanding energy needs, massive amounts of CFA were produced, with estimates of 750 million tonnes in 2015 (Yao et al. 2015) compared to 500 million tonnes in 2005 (USEIA 2014).

Coal is one of the world's main sources of energy and the fifth-largest fossil fuel reserve. After China and the United States, India comes in third place globally with 54.42% of the total electricity produced by coal-fired power plants (Mittal et al. 2012). The country's total coal power consumption increased from 154,664 MW to 374,199 MW between March 31, 2007, and November 30, 2020. Depending on the fuel ratio and the coal's ultimate and proximate characteristics, it can be categorised as anthracite, bituminous, lignite, or sub-bituminous. Bituminous and sub-bituminous coal are currently used in India's thermal power industries. They are primarily extracted from the major coalfields in the states of Madhya Pradesh, Bihar, Orissa, Andhra Pradesh, West Bengal, Maharashtra, Talcher, Godavari Valley, Raniganj, Wardha Valley, and Korba (West and East) (Pandey et al. 2011). There is a significant quantity of coal that is set aside in India's eastern and southern regions. According to Energy Statistics (MOSPI 2019), Jharkhand and Odisha own more over half of the reserved coal, i.e. 26.06% and 24.86%, respectively, of all the states having coal deposits. The Central Electricity Authority of India has released new data showing that the percentage of Coal fly ash (CFA) used has increased from 38 to 78%; the remaining is still dumped in landfills and ash ponds (CEA 2020), as illustrated in Fig. 1.2. The production of CFA is significant, especially in India, which mainly depends on thermal power plants to meet its energy needs. Every year, the nation's coal-fired power plants create about 200 million tonnes of CFA. It is projected to reach approximately 300 million tonnes (MT) by 2022. From the fiscal year 1996–1997 to

2021–2022, the Central Electricity Authority of India monitored the production and use of coal fly ash, as illustrated in Fig. 1.3. The amount of fly ash generated in India increased significantly, from 68.88 MT to 270.82 MT. Initially, just 9.63% of this ash was used in 1996–1997, with only 6.64 MT being reused. However, a noteworthy increase of 77.59% of the fly ash was used in 2019–20. Until 2021–2022, this trend continued, and 259.86 MT were repurposed, achieving an incredible 92.41% utilisation (CEA 2022). The continuously increasing production and use of fly ash indicates a growing commitment to recycling, minimising the impact on the environment, and managing fly ash in a more sustainable manner. By 2031–2032, the Ministry of Power in India projects that it will consume 1800 million tonnes of coal year and generate 600 million tonnes of CFA (Energy statistics India, 2021; Lal et al. 2015).The Ministry of Environment, Forests, and Climate Change has released a number of notifications with the goal of minimising the environmental impact of fly ash by disposing of it scientifically and using it entirely to lessen the need for land and numerous other environmental difficulties (MOEF 1999).

The data on CFA use has been analysed to identify the modes and amounts of CFA utilisation in 2021–2022, as reported by thermal power plants and power utilities. The modes and amounts of CFA use in each sector throughout 2021–2022 are displayed in Fig. 1.4. The Cement Industry Consumed the Most CFA in 2021–2022 (25.41%), followed by the Roads and Flyovers (16.98%), Bricks and Tiles (11.68%), Low-lying Area Reclamation and Filling (13.13%), Mine Filling (6.79%), Ash Dye Raising (5.47%), Concrete (0.82%), Agriculture (0.06%), Other Usage (15.61%), and Unutilized Ash (4.05%) (CEA 2022).

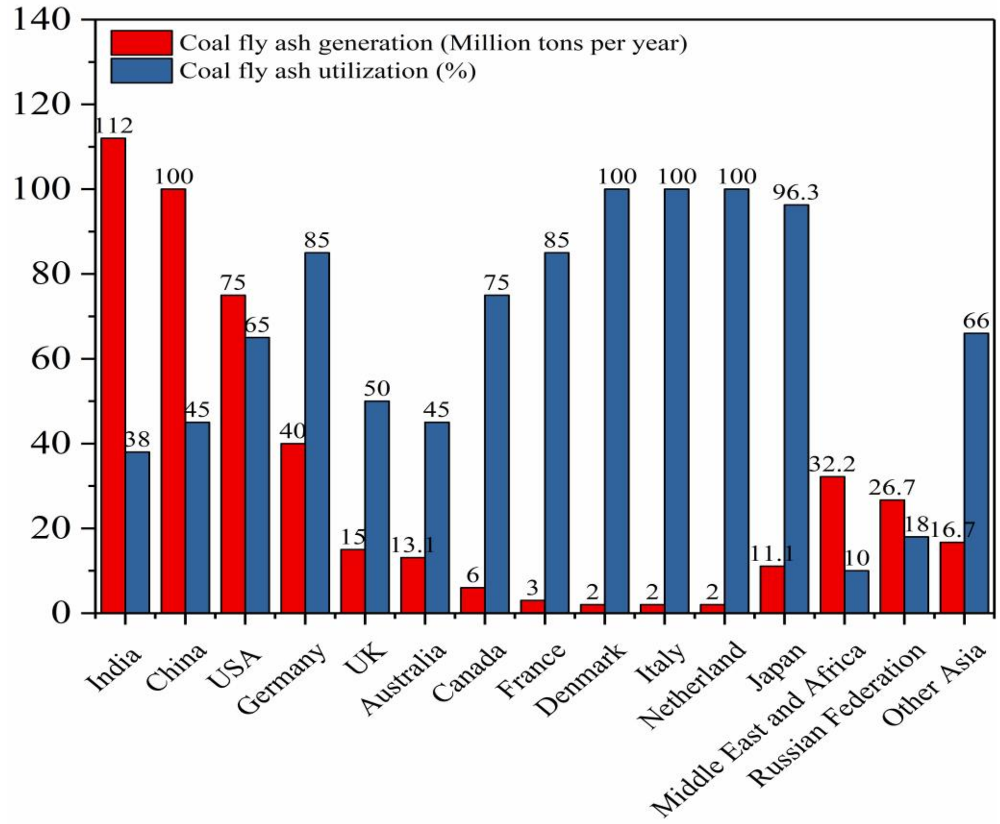

Fig. 1.2. Coal Fly ash (CFA) generation and utilization in the worldwide (CEA 2020)

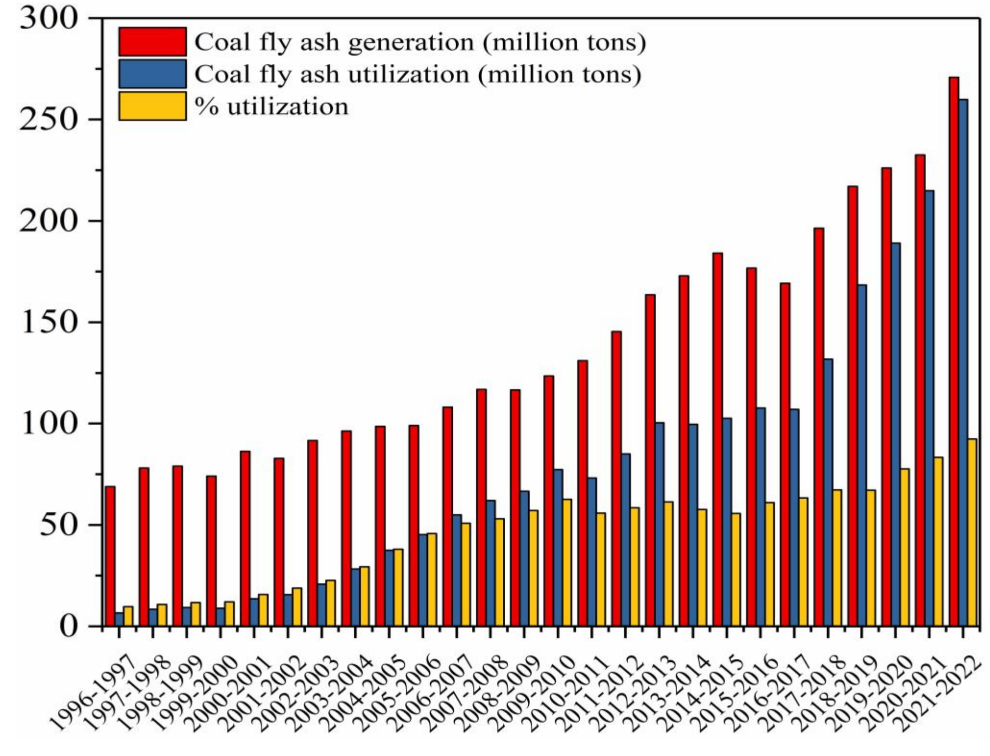

Fig. 1.3. Production and utilisation of Coal Fly Ash between 1996–2022 (CEA, govt. Of India).

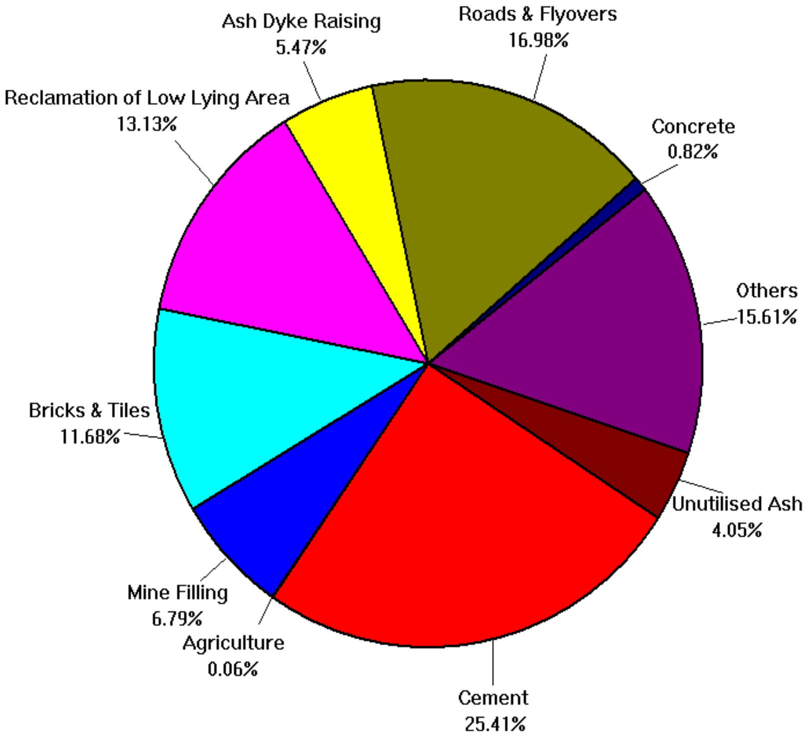

Fig. 1.4. Central practices of CFA use in 2021–22 (CEA, Govt. of India)

1.1.3 Scenario of Nanotechnology

Nanotechnology has grown significantly as an interdisciplinary field during the past 20 years, particularly in the last ten years. Although it is a relatively new field, nanotechnology is not a particularly inventive application of physics, biology, chemistry, or engineering (Wilson et al. 2008). The primary reason for this is the advancement in our comprehension of the physics and chemistry of materials at the nanoscale, which has led to the creation of specialized applications for common engineering-level problems (Steyn 2009). A talk by physicist Richard Feynman titled "There's Plenty of Room at the Bottom" was given in December 1959 at the American Physical Society meeting at the California Institute of Technology. This talk laid the groundwork for the ideas and concepts that would eventually form the basis of nanoscience and nanotechnology (Feynman 1960). The manipulation of matter with at least one dimension scaled between 1 and 100 nm is the definition of nanotechnology, as established by the National Nanotechnology Initiative of the United States. Engineered nanomaterials (ENMs) are materials that are purposefully designed to consist of distinct structural and functional components, either within or at the surface. Many of these components will have one or more dimensions of the order of 100 nm or less (Nel et al. 2006; Kreyling et al. 2010). Researchers have been interested in applying nanotechnology and nanomaterials in a variety of fields in recent years; researchers in the domains of environmental studies, geotechnical engineering, and civil engineering have already shown an interest in these technologies (Zhu et al. 2004; Shan et al. 2009; Changizi and Haddad 2016; Kutanaei and Choobbasti 2016). Nanoscience and technology are considered as the most significant scientific and technological field of the twenty-first century, with the potential to transform the engineering sector and help to satisfy the need for sustainable development (Pacheco-Torgal and Labrincha 2013). When using nanomaterials at greater or smaller scales, their performance is improved in comparison to the other additives. This is a result of their nanoscale effects on the materials. In addition to traditional stabilization materials, nano dimension stabilizers are being used in soil stabilization (Harsh et al.2023; Iranpour 2016). Because more atoms and molecules are visible in the area where smaller particles are found, surface characteristics become more important and dominant while mass properties become less important. Nanoparticles, even at very low concentrations, can dramatically alter the engineering characteristics and behaviour of soils due to their enormous specific surface area and surface charges (Bahmani et al. 2014; Khodaparast et al. 2021; Munda et al. 2024; Karimiazar et al. 2022).

There are significant differences in the physical properties and effectiveness of nano-, micro-, and macro-silica in soil stabilization applications. Nano-silica, with its extremely small particle size and high specific surface area, exhibits high reactivity and accelerates pozzolanic reactions when mixed with soil, leading to rapid strength gain and significant improvement in soil microstructure by filling micropores and reducing permeability. In contrast, micro-silica (commonly known as silica fume) also has pozzolanic properties but with a larger particle size compared to nano-silica, making it less reactive but still effective in improving strength and durability over time. Macro-silica, which typically consists of larger, inert silica particles such as sand or quartz powder, primarily acts as a filler and contributes to mechanical stabilization rather than chemical enhancement. The primary component of bentonite and nano silica materials, which are mostly inert and non-toxic, is silicon dioxide, much like natural clay. Therefore, using bentonite and nano silica to improve soil is both safe and environmentally friendly. Soil improvement using nanoparticles is more economical, environmentally friendly, and causes very little disturbance of the earth as compared to traditional grouting processes (Huang et al. 2016).

1.1.3.1 Nanotechnology Application in Geotechnical Engineering

According to earlier research, there are a number of benefits of utilizing nanomaterials directly in soil stabilization that can offer a number of benefits over conventional treatment techniques. Water seepage and thermally induced crack failures are two examples of road failures that could be controlled by nanomaterials. The hydrophobic behaviours of the treated building materials, which reduces the damage from water seepage by covering the entire road from top to bottom in a waterproof layer. There are several options to use readily available local materials that would not normally meet performance criteria in their natural state when using nanoparticles as a preventive engineering solution. This advances the delivery of road transport infrastructure projects that are secure, long-lasting, cost-effective, and environmentally friendly. It also supports sustainable civil engineering practices (Ugwu et al. 2013). The pore spaces of cracks and the slip zone of a loess landslip were filled at China's Lvliang Airport using grouting materials based on fly ash and Nano-SiO_2. While also withstanding tensile stress, the grouting materials utilized at the top surface of the slope are sufficiently able to minimize the development of pore water pressure caused by rainwater infiltration. In addition, grouting materials applied to the slip surface zone can promote the development of a denser structure between the grout and the loess soil, reducing the force of sliding down the slope and preventing landslides (Gao et al. 2020). Fig. 1.5 shows the schematic diagram of fissures in Lvliang Airport grouted into the fissures at the top of the slope and within the structure. The tensile fissures at the top of the slope are filled with filling material. The slurry then follows the fracture into the interior, filling the fissures and entering the surrounding soil, which has the ability to withstand the tensile stress on the slope's uppermost portion and lower the pressure of pore water.

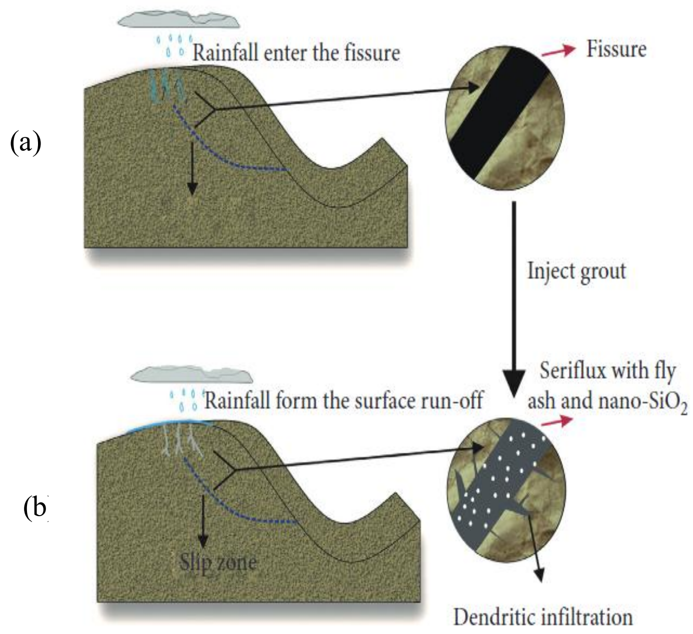

Fig. 1.5. Schematic diagram of fissures in Lvliang Airport: (a) before grouting; (b) after grouting (Gao et al. 2020).

The addition of slag, Nano-SiO_2, and lime to the silt subgrade resulted in enhanced cation exchange, pozzolanic reaction, and hydration of the soil particles. As a result, the soil's porosity was reduced and its intermolecular force became greater. After that, it was applied to maintain the silt subgrade in order to meet the needs of highway construction (Wang et al. 2021). When Nano-SiO_2 was employed for pre-grouting, particularly in the sandy soil grouting approach, because to its adjustable setting time, low permeability, and non-toxicity to the environment. It has remarkable potential and practical field applications as a grouting strengthening material in coastal locations (Cheng et al. 2022). The results of the full-scale field test successfully illustrated that the amount of settlement caused by the liquefaction of loose sand deposits was reduced by the grout treatment injected with colloidal silica. After treating around 2 m of a 9 m thick liquefiable zone, it was shown that the settlement had considerably decreased (Gallagher et al. 2007). At Fukuoka International Airport, colloidal silica was successfully injected using a controlled curved drilling technique, protecting the runway surface against liquefaction, and developing around 100 m of the runway (Rasouli et al. 2016). Fig. 1.6 illustrates the Schematic diagram of two methods of permeation grouting method.

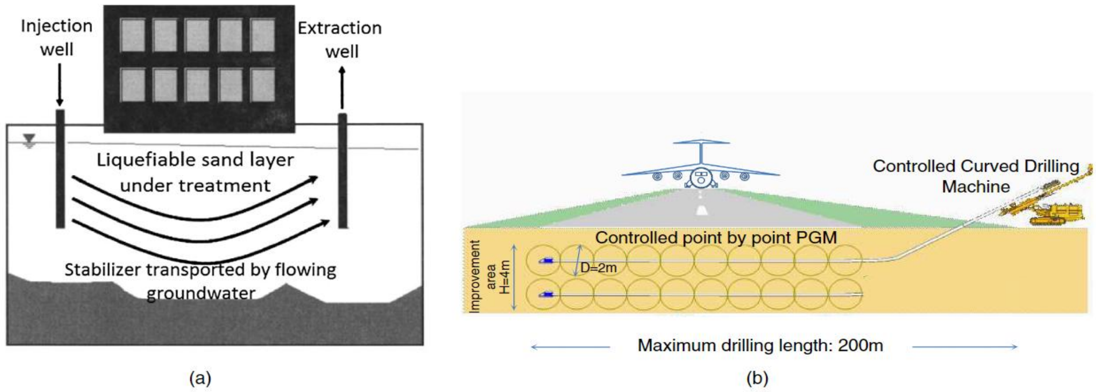

Fig. 1.6. Schematic illustration of two methods of permeation grouting method (PGM): (a) uncontrolled grouting (Gallagher et al. 2007); (b) an example of controlled grouting (drilling machine image courtesy of Penta-Ocean Construction Co., Ltd.).

1.2 AN OVERVIEW AND PROBLEM IDENTIFICATION

The design and construction of infrastructure commonly encounter clayey soil, which has a high degree of compressibility and insufficient bearing capacity. Numerous methods of soil improvement, including chemical stabilization, soil reinforcement, lowering the water table, etc., can be used to treat weak soils and modify their characteristics. One of the most widely used techniques for ground development throughout many millennia has been soil stabilization with conventional additives. The use of nanomaterials as soil stabilizers has been proposed by numerous researchers recently due to the development of science and technology. Many researchers are still investigating the use of nanoparticles as soil stabilizers, despite the fact that their application in many geotechnical engineering divisions has not yet shown success. The most widely utilized nanomaterials are carbon nanotubes, colloidal silica, Nano-SiO_2, nano-TiO_2, Al_2O_3, and nano-clay (Taha and Taha 2012; Ghasabkolaei et al. 2017; Krishnan and Shukla 2019; Barbhuiya and Hasan 2021). However, Nano-SiO_2 is regarded as one of the materials that is utilized the most frequently among all the additives. Because of its low environmental impact, cost-effectiveness, and sustainable development, the soil improvement method based on silica nanoparticles can take the place of traditional stabilizers like cement and lime in light of environmental concerns and subsurface contamination (Kannan and Sujatha 2022).

The treatment and disposal of the ash produced by coal-based thermal power plants is a major challenge faced globally. This issue is complicated by the high ash concentration (30–50%) of Indian coal. In India, ash ponds cover 65,000 acres of land, and by 2020, it is expected that production will have surpassed 225 million tons (Divitkumar et al. 2022). The Central Pollution Control Board report from June 2023 states that 271 million tons of coal ash are produced each year (CEA 2023). In order to reduce its negative environmental effects and encourage sustainable practices in the energy industry, this substantial volume highlights the urgent need for efficient management and recycling techniques. The need for a big storage area and the safe disposal of the ash without negatively impacting the environment are the main issues. Therefore, rather than disposing of the ash, efforts are being undertaken to use it. The coal ash can be used in large quantities for geotechnical engineering applications such as sub-base construction, backfill, and the embankment construction. For this, a thorough understanding of the engineering, chemical and physical properties of the coal ash is needed. The pozzolanic reactions between the soil and the calcium-based addition are primarily responsible for fly ash's efficacy as a subgrade treatment. In pozzolanic processes, silicate and aluminate clay minerals interact with calcium hydroxide transported by the water to generate calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) (Sargent 2015). By using fly ash more extensively, its waste disposal issues can be resolved and the need to produce cement and other calcium-based soil stabilization additives can be decreased.

The primary goal of this research is to explore the chemical, physical characteristics of the high plasticity clay soil and to investigate its strength performance by using Nano-SiO_2 (NS) and fly ash as additives. The dynamic properties of the soils as established by the laboratory tests are essential to handle the earthquake engineering problems from a geotechnical perspective. Hence, dynamic characterization of the composite material has also been investigated.

1.3 OBJECTIVES

This research is focussed on the utilization of fly ash and Nano-SiO_2 (NS) as a viable stabilizing agent to enhance the strength characteristics of the high plastic clayey soil and serve as a sustainable alternative to cement and lime. The main objectives of this study are as follows.

- To study the physical, morphological, mineralogical, chemical, and geotechnical characteristics of the collected clayey soil sample.
- To study the strength characteristics of clayey soil treated with Nano-SiO_2 and fly ash.
- To study the dynamic characteristics of clayey soil treated with Nano-SiO2 and fly ash under different amplitude of cyclic shear strain.
- To study the small-strain stiffness characteristics of clayey soil treated with Nano-SiO_2 and fly ash under low-strain condition.
- To develop normalized modulus reduction and damping ratio curve for clayey soil treated with Nano-SiO_2 and fly ash.
- To study the carbon footprint and cost analysis of clayey soil treated with Nano-SiO_2 and fly ash.
- To study the utilization of Nano-SiO_2 and fly ash treated clayey soils in various civil engineering applications.

1.4 SCOPE OF THE STUDY

The scope of the current investigation has been thoroughly explored after examining the previously indicated research objectives. This study aims to investigate the strength performance of clayey soil treated with Nano-SiO_2 (NS) and fly ash under both static and dynamic loading circumstances. Few studies have been conducted on the dynamic behaviour of soil treated with Nano-SiO_2, despite the fact that the static strength behaviour of the soil has been extensively explored. Several static triaxial (Unconsolidated Undrained) and unconfined compressive strength (UCS) laboratory tests were conducted to determine the optimum additive dosages. A series of bender elements (BE) tests were carried out to find the relationship between shear strength (τ) and small-strain shear modulus (G_{max}) for the purpose of seismic analysis of geotechnical engineering challenges. The dynamic properties of the clayey soil, both with and without treatment, were then evaluated using multiple sets of cyclic triaxial tests over the duration of 28 days curing period. All the experiments were performed under the optimal compaction conditions for the soil specimen. This research aims to provide the normalized modulus reduction (G/G_{max}) and damping ratio curves by utilizing the bender element (BE) and cyclic triaxial (CTX) test results. The proposed curves can be applied to fly ash and Nano-SiO_2 treated clayey soil for dynamic response analysis or soil behaviour modelling.

1.5 ORGANIZATION OF THE THESIS

The thesis is divided into several chapters that provide a thorough experimental study, ranging from basic to advanced. The overall problem illustration and a summary of previous studies that took various materials and equipment into consideration are presented at the beginning of these chapters. The chosen source material was next subjected to chemical and geotechnical characterization. The advanced experimental research for various soil combinations was carried out based on fundamental properties. All of the chapters have been summarised in the parts that follow.

Chapter I describes the background, motivation towards this research topic, problem identification, objectives, and scope of the research.

Chapter II provides an overview of previous research on the properties of soil treated with Nano-SiO_2, including its physical, morphological, chemical composition, mineralogical, geotechnical, durability, and dynamic characteristics. It also discusses the performance of soil treated with fly ash, the challenges in using nanomaterials in the field to stabilize the clayey soil and identifies research gaps for further study.

Chapter III described the source of soil sample collection, and the method used to prepare the samples in the current investigation. A number of experimental programs were illustrated through graphical representation, starting with the chemical characterisation and subsequently the geotechnical characterisation, static and cyclic triaxial tests. Additionally, this section described the reasoning for consideration of different parameters. Furthermore, a thorough description of the testing technique and the basic principles of the bender element test and cyclic triaxial test have been provided.

Chapter IV described the chemical characterization of both treated and untreated soil using X-ray diffraction (XRD), X-Ray fluorescence (XRF), scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX), and Fourier Transform Infrared (FTIR) Spectroscopy tests.

Chapter V discussed the findings of geotechnical and static triaxial tests results of the untreated soil and the soil treated with the combination of fly ash and nano silica. It includes particle size distribution, compaction behaviour, consistency limits, permeability, consolidation, UCS, triaxial test, and CBR tests. For better understanding, the results were presented in tabular, graphical, and pictorial form.

Chapter VI discussed about the dynamic characterization of the parent clayey soil and the soil treated with optimised fly ash and nano silica using consolidated undrained cyclic triaxial test under various cyclic shear strain amplitudes.

Chapter VII discussed about the normalization of the high-strain shear modulus with the small-strain shear modulus (G_{max}). Moreover, a normalized modulus reduction (G/G_{max}) and damping ratio curves of both treated and untreated soil samples with different cycle strains were developed. Furthermore, the relationship between the small-strain shear modulus (G_{max}) and shear strength (τ) of the treated soil was evaluated.

CHAPTER VIII discussed about the Carbon footprint, Cost analysis and field applications of the stabilized clay soil.

CHAPTER IX summarizes the research study, highlights the major findings, limitations of the current study, and further future research directions are suggested.

Finally, the references used in the present study are organized alphabetically.