Chapter 3

Materials and Methods

3.1 General

The chapter describes a brief overview of the experimental methodology that has been followed in the current study. The chapter discusses the materials used, experimental planning, and fabrication of apparatus in detail. A description of the procedure of sample preparation, curing conditions, and sampling techniques were also informed in this chapter. The different types of tests carried out to assess the index properties and strength performance of different stabilisers on alkali interacted soils were also elucidated. The curing periods of samples were also stated and the procedures involved in the tests were described. The methodology adopted in the present study is described step-wise in the following sections. Each step in the methodological flow chart is elaborated in the subsequent sections.

3.2 Material Selection

The materials which were used in the experiments and methodology adapted to determine their properties are mentioned below.

3.2.1 Soil

The soil samples used in the study were collected locally in Varanasi (25°19'0.1" N, 83°0'37.5" E) within the Banaras Hindu University Campus. The soil was cleaned by removing unwanted foreign materials and sieved through the 4.75mm sieve and then stored in separate stacks. It was oven-dried at 105 ± 5^{o}C for moisture removal before its use in the experimental programme. The soil as shown in Fig. 3.1 appears yellowish in colour and contains mostly fine particles on visual examination. Different tests were performed to determine the geotechnical properties of the soil used in the study. The characteristics of the soil were determined as per relevant specifications and the details of the tests are stated below in the subsequent sections.

Figure 3.1: Soil used in the study

3.2.2 Geotechnical Tests

The procedure of different geotechnical tests which were carried out on the soil samples in this study are discussed in detail in this section.

3.2.2.1 Particle Size Distribution

The grain size of soil has a significant influence on its engineering properties. Wet sieving was performed in which the soil samples were washed through a 75 µm sieve and then the coarser and finer particles were collected and oven-dried separately. In addition, the Particle size distribution was determined using mechanical sieving and hydrometer analysis as per the ASTM D6913 and ASTM D7928 guidelines respectively. Finally, the results are plotted on a semi-log curve between percentage finer and particle size in mm as shown in Fig. 3.2. According to the Unified Soil Classification System (USCS), the soil has been classified as clay with low compressibility (CL).

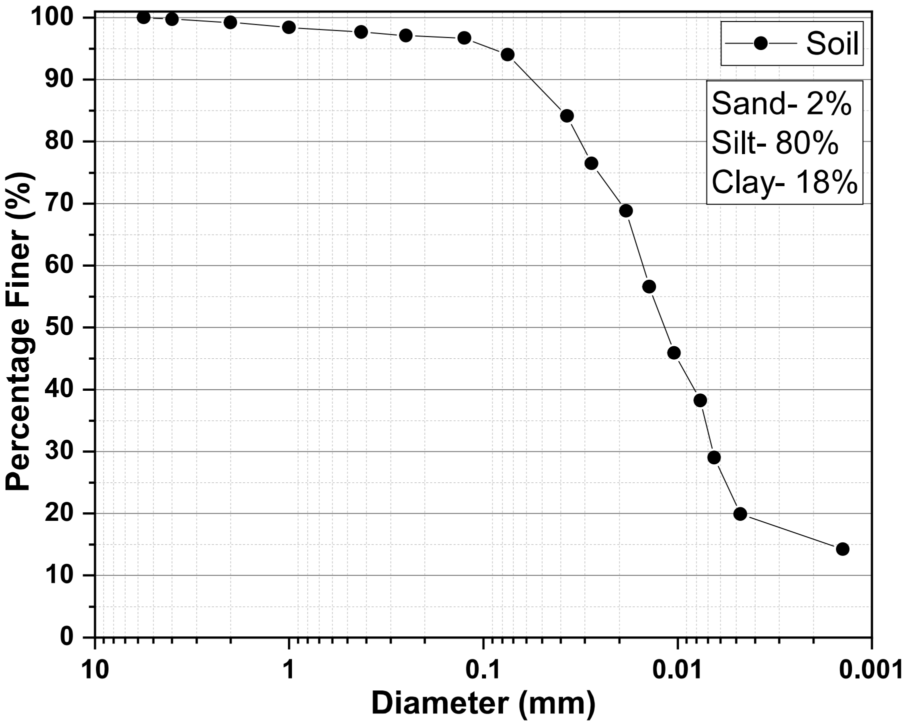

Figure 3.2: Grain size distribution of soil

3.2.2.2 Atterberg Limits

Atterberg limits refer to the relative ease with which a soil can be deformed. It is a property associated only with fine-grained soil. It divulges the four different states such as solid, semi-solid, plastic and liquid state that is also associated with the physical and mechanical behaviour of soil. The liquid limit and plastic limit of soil was determined as per ASTM D4318-17e1 guidelines. The liquid limit is defined as the minimum water content at which soil tends to flow under the application of a negligible shearing force. The plastic limit is the minimum water content at which soil changes from plastic to a semi-solid state. The difference between its liquid and plastic limits gives the value of the plasticity index. The liquid limit and plastic limit of soil was found 35% and 22.23% respectively.

3.2.2.3 Specific Gravity

specific gravity is used to express the density of soil to that of water. The specific gravity of the soil was determined at 25^oC as per ASTM $D854-14$ specifications using a pycnometer. Firstly, the weight of the cleansed and overdried empty pycnometer with its cap was taken

(M1). Approximately 200 to 250 gm of oven-dry air-cooled soil sample was transferred to the pycnometer and the weight of soil with the pycnometer was recorded (M2). After that, a sufficient amount of de-ionized water was added to the pycnometer so as to fill the voids completely. The soil-water mixture is stirred well and left for 5 to 6 hours to soak the soil completely. Fill the pycnometer with distilled water again, the cap was screwed to the mark. A vacuum pump was connected for 10-15 minutes to remove the entrapped air after which the pycnometer was filled completely with water up to the mark and its weight was recorded (M3). Finally, the pycnometer was completely filled with water only and its weight was again recorded (M4). The specific gravity of soil was determined using the relation expressed in the equation. The same procedure is repeated 2 to 3 times, and the specific gravity of the soil is reported as the average of three readings. In the present study, the specific gravity of soil was found as 2.5 after averaging three values.

3.2.2.4 Compaction Characteristics

The compaction test was conducted to determine the maximum dry unit weight and optimum moisture content of the soil. The compaction test was carried out with ASTM D698 guidelines. The results of the compaction test are presented as dry density vs water content and from the plot, the maximum dry density and the optimal water content are determined. These values were used in preparing samples for the unconfined compressive strength test and triaxial test. The compaction curve of soil is shown in Fig. 3.3. The value of maximum dry density and optimum moisture content of soil used in the study is 1.66 g/cc and 16.4%.

3.2.2.5 Unconfined Compressive Strength

Unconfined compressive strength is a simple, expeditious, and extensively used laboratory method to access the shear strength of the soil. The unconfined compressive strength of soil is defined as the load per unit area of cylindrical specimen of the standard dimension of a soil mass fails in a simple compression test. The unconfined compressive strength test was performed in accordance with ASTM D2166. For preparing the standard soil specimen of unconfined compressive strength, the required amount of soil sample corresponding to chosen maximum dry density is mixed thoroughly with optimum water content. After mixing the soil sample, it was compacted in a cylindrical metallic mould having a size 38

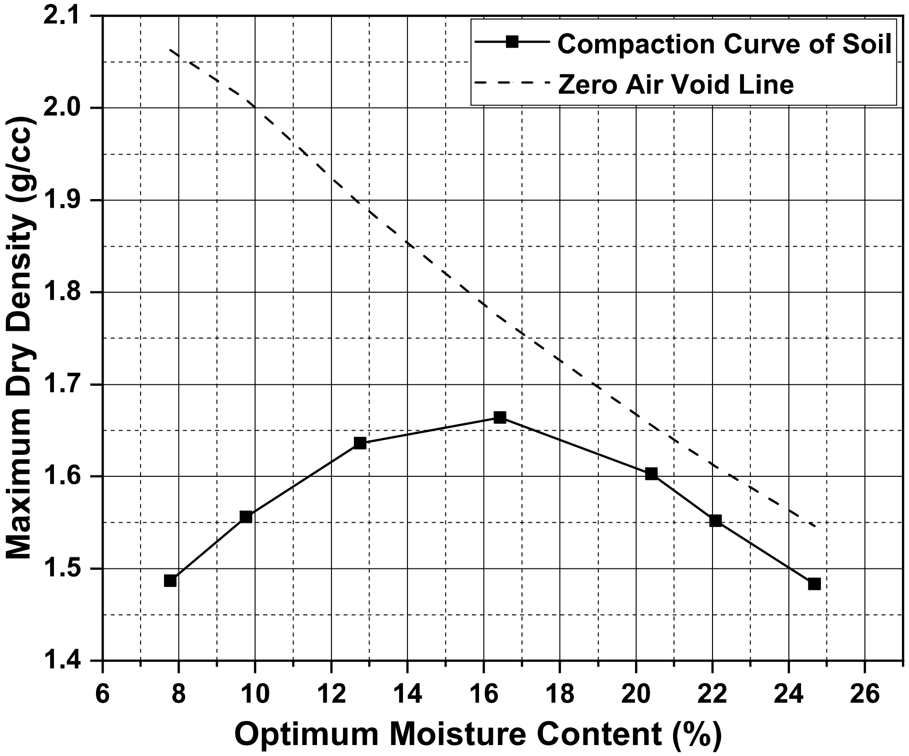

Figure 3.3: Compaction Curve of Soil

cm inner diameter and 76 mm height in three equal layers to the targeted unit weight. The compacted soil mixture was extracted from the mould with universal hydraulic sample extractor machine. The extracted sample was then placed in air tight polythene bag for a desirable curing period in a desiccator at standard temperature by maintaining the relative humidity of more than 95%. At the end of the curing period, the samples were tested in a loading frame of capacity 50 kN capacity at a strain rate of 1.2 mm per minute with a proving ring of known capacity. The average of three test values is reported as UCS value of corresponding soil sample. The unconfined compressive strength of soil is 141 kPa.

3.2.2.6 Triaxial Test

The unconsolidated undrained triaxial (UU) test was conducted in accordance with ASTM D2850 to evaluate shear parameters. Determination of the shearing strength of soil involves the plotting of the failure envelope. The method of sample preparation for this test is similar to that of unconfined compressive strength test by maintaining the aspect ratio 0.5, i.e, 38 cm diameter and 76 mm height. Samples were tested for different cell pressures and loaded at a strain rate of 1.2 mm/minute which causes a deformation in the soil in the vertical direction resulting in shear failure. The vertical stress applied by load frame called deviatoric stress was recorded through the proving ring. By recording the corresponding deviatoric stress for three different confining pressures, the Mohr failure envelope was drawn. A curve tangent to these envelopes gives the value of cohesion and angle of internal friction. The value of cohesion of the soil was found to be 55 kPa and the angle of internal friction was 13^o respectively.

3.2.3 Ground Granulated Blast-Furnace Slag (GGBFS)

GGBFS is a by-product of iron and steel-making industries that is produced in the blast furnace during the quenching process of molten iron slag through water or stream. The slag is then dried and grounded into fine powder. The amount of slag production ranges from 300 to 540 kg per tonne of pig or crude iron produced, whereas in steel making 150 to 200 kg per tonne of slag is generated per tonne of liquid steel. It appears to be grey in colour (Fig. 3.4) and an amorphous silt size particle that possesses excellent hydraulic cementitious features due to the presence of silicates and aluminosilicates of calcium. The physical and chemical properties of GGBFS are shown in Table 3.1.

Figure 3.4: GGBFS used in this study

According to the Indian minerals yearbook 2019 (Part- II), about 24 million tonnes

Table 3.1: Physical properties and chemical compositions of GGBFS

Physical Properties		Chemical Compositions	
Properties	Values	Compositions	Percentage
Specific Gravity	2.85	Silicon dioxide (SiO_2)	35.84
Liquid Limit (%)	29.5	Aluminium oxide (Al_2O_3)	13.07
Clay, <2µm (%)	4.8	Titanium dioxide (TiO_2)	0.61
Silt, 75-2 µm (%)	93.2	Ferric oxide (Fe_2O_3)	1.18
Sand 4.75mm to 75 µm (%)	2	Magnesium oxide (MgO)	4.51
MDD (g/cc)	1.57	Calcium oxide (CaO)	32.38
OMC (%)	22.5	Sodium oxide (Na_2O)	0.5
UCS (kPa)	157	Potassium oxide (K_2O)	0.75

of blast furnace slag and 12 million tonnes of steel slag were produced by the steel industry annually which is expected to be increased by 45 to 50 million tonnes (Blast furnace slag) and 15-20 million tonnes (steel slag) by the end of the year 2030. Consumption of such a huge quantity of blast furnace slag is becoming an increasing concern for recycling and waste management. Due to its cementitious and pozzolanic properties, it has been used in many fields such as cement manufacture, landfills, railway ballast, concrete aggregate, and asphalt paving. Besides these applications, one of the important uses is the stabilisation of problematic soil. In this thesis, GGBFS has been used in different percentages of GGBFS for the stabilization of alkali interacted soil which is discussed in brief in the subsequent section.

3.2.4 Alccofine

Alccofine is light grey (Fig. 3.5) micro fine particle size material that possesses hydraulic and cementitious properties. It is obtained from the materials of the iron ore industry. Alccofine is mainly composed primarily of calcium silicates. It has come in market series i) Alccofine 1100 series ii) Alccofine 1200 series. Alccofine 1100 series contains more calcium silicates than 1200 series. In the present study 1100 series of alccofine have been used for stabilization of alkali interacted soil. Alccofine 1100-S was made available by Counto Microfine Products Pvt. Ltd., Sattari, Goa for the current research purpose. The physical properties and chemical composition of alccofine are shown in Table 3.2.

Figure 3.5: Alccofine used in this study

Table 3.2: Physical properties and chemical compositions of Alccofine

Physical Properties		Chemical Compositions	
Properties	Values	Compositions	Percentage
Specific Gravity	2.87	Silicon dioxide (SiO_2)	33.64
Liquid Limit (%)	23.3	Aluminium oxide (Al_2O_3)	21.21
Clay, <2µm (%)	6.8	Titanium dioxide (TiO_2)	0.41
Silt, 75-2 µm (%)	91.2	Ferric oxide (Fe_2O_3)	1.21
Sand, 4.75mm to 75 µm (%)	2.0	Magnesium oxide (MgO)	8.62
MDD (g/cc)	1.51	Calcium oxide (CaO)	34.18
OMC (%)	20.5	Sodium oxide (Na_2O)	0.15
UCS (kPa)	132.0	Potassium oxide (K_2O)	0.45

Due to the presence of high Calcium Oxide (Cao) content in alccofine, it has been used for soil stabilization. It behaves as a pozzolanic material, which helps in reducing the permeability of the soil and creates dense packing in soil; thus, reducing the water content and ultimately increasing the compressive strength of the soil.

3.2.5 Chemical Stabilizer

In the current research, three chemical stabilizers were used in different combinations for the stabilization of alkali-interacted soil with the aspect of controlling the alkali-induced heaving. These chemical stabilizers are selected on the basis of the efficiency of the chemical in improving the properties of contaminated soil, solubility in water, cost analysis, eco-friendly and etc. The details of chemical stabilizers and their combinations used in the study are discussed below:

3.2.5.1 Enzyme-Induced Carbonate Precipitation (EICP)

Enzyme-induced carbonate precipitation (EICP) is one of the new and innovative bio-inspired techniques that can be employed in-situ for ground improvement. The eco-friendly nature of EICP draws the attention of many researchers for the stabilization of contaminated soil as well as problematic soil. The main principle involves in the use of EICP is the precipitation of calcium carbonate ($\mathrm{CaCO_3}$) in the void of soil via the hydrolysis of urea ($\mathrm{CO(NH_2)_2}$) into ammonium ($\mathrm{NH_4^+}$) and carbonate ($\mathrm{CO_2^{3-}}$) ions catalysed by the urease enzyme. The smaller size of the urease enzyme crystals used in the EICP process makes it more propitious in improving the strength of problematic soil than any other methods. The wider application of EICP process in solving many environmental, construction, geotechnical and civil engineering problems, such as improving soil strength, reducing soil liquefaction potential, surface erosion control, reducing permeability, heavy metal contaminant remediation, and so on shows the greater potential of its applicability in the field. The major chemical constituents involved in the EICP process are urease enzyme, urea ($\mathrm{CO(NH_2)_2}$) and calcium chloride ($\mathrm{CaCl_2}$). The reagent-grade calcium chloride dihydrate and urea (≥ 99)were used for preparing EICP solution. Jack beans urease enzyme powder with a reported activity of 3500 units/g at room temperature was also purchased from CDH Chemicals. To induce cementation with EICP, a mix of enzyme and cementation solution of urea and calcium chloride of preferred concentration was used. The involved chemical reactions between all combinations are shown in equations (3.1), (3.2) and (3.3) as follows:

$$CO(NH_2)_2 + H_2O \rightarrow NH_4^+ + CO_3^{2-} \tag{3.1}$$

$$CaCl_2 \rightarrow Ca^{2+} + 2Cl^- \tag{3.2}$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3(Precipitate) \tag{3.3}$$

In this study five combinations of EICP were used based on the literature review that gives maximum precipitation of $CaCO_3$ as shown in Table 3.3.

Table 3.3: Test combinations of EICP for stabilizing alkali interacted soil

Test Combinations	Urea (Molarity)	$CaCl_2$ (Molarity)	Urea: $CaCl_2$	Enzyme (g/l)
C1	1	0.83	1:1.2	6
C2	1	0.67	1:1.5	5
C3	1	0.57	1:1.75	3
C4	1	0.83	1:1.2	5
C5	1	0.57	1:1.75	5

3.2.5.2 Sodium Silicate

Sodium silicates are colourless, non-toxic, non-corrosive, and inexpensive solution which is stable in a neutral and alkaline environment. The sodium silicate solution used in this study was purchased with a purity of 99%. The chemical composition of sodium silicate is Na_2O (13%) and SiO_2 (32.5%) by weight and the ratio of Na_2O and SiO_2 is 1:2.5 as specified by M/s. CDH Chemicals.

Sodium silicate solutions have been successfully used as a grouting material in improving the properties of contaminated soil because of their environmental compatibility and safety. In the past, sodium silicate has been used with a different chemical to develop a stable grout material. In this study, different percentages of sodium silicate solution are used accompanied by 1 molar calcium chloride solution for the treatment of alkali interacted soil. The test combinations used in the study is shown in Table 3.4.

The injection of the aqueous solution of sodium silicate with calcium chloride reacts to form a colloid which polymerizes further to form a gel. The silicate gel binds the soil particle together or fills the voids of soil ultimately increasing the strength, stiffness, and reduced permeability of the soil.

Table 3.4: Test combinations of sodium silicate

Test Combinations	Sodium Silicate (%V/V)	$CaCl_2$ (Molarity)
T1	10	1
T2	20	1
T3	30	1
T4	40	1
T5	50	1

3.2.5.3 Sodium Carbonate

Sodium carbonate is an inorganic compound that forms from the combination of sodium and carbon dioxide. It is an environmentally friendly and safe inorganic calcium-based chemical compound used as a soil stabilizer. The sodium carbonate used in the study is purchased from M/s. CDH chemical. In this study, the different molarity of sodium carbonate solution is used accompanied by 1 molar calcium chloride solution for the treatment of alkali interacted soil. The test combinations used in the study is shown in Table 3.5.

Table 3.5: Test combinations for sodium carbonate

Test Combinations	Sodium Carbonate (Molarity)	$CaCl_2$ (Molarity)
M1	0.5	1
M2	0.8	1
M3	1	1
M4	1.2	1
M5	1.5	1

The chemical reaction between sodium carbonate and calcium chloride forms calcite precipitation in the voids of soil particles. The calcite precipitate helps in either making a strong bond between particles or themselves get hardened and causes improvement in the strength and geotechnical properties of soil.

3.2.5.4 Calcium Chloride

Calcium chloride is white crystalline inorganics salt that has been used for stabilization of problematic soil. The calcium chloride pellets used in this research were purchased from M/s. CDH chemicals hold with 99% purity. The 1 molar $CaCl_2$ solution was used with a different stabilizer for the treatment of alkali interacted soil. The hygroscopic properties of $CaCl_2$ make it more effective for the stabilization of soils. The ready dissolvability properties of $CaCl_2$ in water and the generation of an adequate amount of calcium ions in cation exchange reaction make it more suitable for the stabilization of soil. It also has the ability to agglomerate fine particles and binds them together which improves the properties of soil such as strength, compressibility, permeability and etc.

3.2.6 Alkali Solution

Commercially available sodium hydroxide pellets are purchased from CDH with a molar weight 40.00 g/mol, density 2.13 g/cm^3, and solubility in water is 10%. Three different alkali (NaOH) solutions of 8M, 12M, and 16M were used in the present study. The alkali solution was prepared by dissolving the required amount of sodium hydroxide pellets in distilled water and agitated for 30 minutes until a uniform solution was achieved. The mixing of sodium hydroxide pellets in water releases heat, therefore the solution is left undisturbed for 2-3 hours to cool down to room temperature.

3.2.7 Sample Preparation

In this study, the effect of three different moralities (8M, 12M, 16M) of NaOH solution with soil on heaving and its geotechnical properties were evaluated. For this, the collected soil was cleaned and oven dried to remove the impurities and excess moisture present in the soil. After oven drying soil sample was crushed and sieved through a 4.75 mm sieve and kept in plastic bags. Different concentrations of NaOH solution (8M, 12M, 16M) were then added to sieved soil and continued the mixing process until a uniform and homogeneous mixture was obtained. In order to achieve a uniform interaction of soil with alkali, the mixed soil was kept in sealed polythene bags as shown in Fig. 3.6a for one week. After one week, alkali-interacted soil was air-dried as shown in Fig. 3.6b, crushed and again sieved with 4.75 mm sieve for further use in the determination of various geotechnical properties.

(a) (b)

Figure 3.6: Interaction of alkali solution with soil (a) polythene bag (b) air drying of alkali interacted soil

3.2.8 Mineralogical Studies

The minerals present in the soil not only affect the interaction of soil with alkali but are also important for the bonding between the soil and different stabilizers. The study of mineralogical changes before and after the interaction of soil with foreign material is very necessary from geotechnical point of view. The mineralogical composition of the soil used in this study was determined using X-ray diffraction (XRD) analysis. XRD analysis is a rapid analytical technique used to determine the primary mineralogical components of soil. XRD analysis was done on fine ground soil using Rigaku Miniflex 600 Desktop X-Ray Diffraction System. The data range for analysis was taken between $5^o 2\theta$ to $80^o 2\theta$. X-ray diffractograms (plots between intensity (counts) and 2θ values) of the soil were drawn and the prominent peaks in the observed pattern were indexed using JCPDS software.

3.2.9 Morphological Studies

The morphological study of soil is very important for the visual analysis of change in microstructure after the interaction with alkali and stabilizers. The EVO - Scanning Electron Microscope MA15 / 18 was employed for characterizing and examining the morphology of soil specimens, alkali interacted soil and stabilized soil. For this, a small amount of oven-dried finely grounded sample is mounted on the tape glued to the flat surface of the gold- coated SEM stub and sputter. The photomicrographs of soil were taken at different resolution levels for examining the variation in the crystal structure of soil before and after treatment.

3.2.10 Electrokinetic Model Set-up

The analysis of alkali induced heaving behaviour of soil was carried out in large scale experimental electrokinetic model. The main purpose of fabrication of large-scale electrokinetic model is to simulate the alkali induced heaving behaviour of soil similar to that of field conditions. For this, two large scale electrokinetic models that are i) Rectangular electrokinetic model ii) Circular electrokinetic model was fabricated. However, for the treatment of alkali interacted soil using chemical stabilizers a bench scale electrokinetic model was fabricated. The detailed description of both the model's large scale and bench scale electrokinetic models are discussed below.

3.2.10.1 Rectangular Model Tank Equipped with ElectroKinetics

The schematic of the elevation and plan of the model testing tank has been shown in Fig. 3.7, Fig. 3.8 and Fig. 3.9 shows the image of rectangular EK model showing the position of dummy electrode, dial gauge and proving ring. The rectangular testing tank was fabricated using brick masonry with dimension 1300 mm x 750 mm x 1000 mm. The tank was divided transversely into three parts comprising of three chambers, namely, the anode chamber, cathode chamber and the soil chamber. The length of the soil chamber was 1000 mm, while that of both the electrolyte chambers was 150 mm. A 20 mm thick perforated acrylic sheet was placed between the electrolyte chamber and soil chamber to ensure a uniform flow of the electrolyte. The top surface was kept open where the soil heaving was measured.

Dial gauges were placed at nine different locations at the top soil surface as shown in Fig. 3.9b to measure the surface heaving. Nine-dial gauges were placed in sets of three at a distance of 250 mm, 500 mm and 750 mm from the anode. Three proving rings were placed at the central line to measure the heaving pressure exerted by the soil.

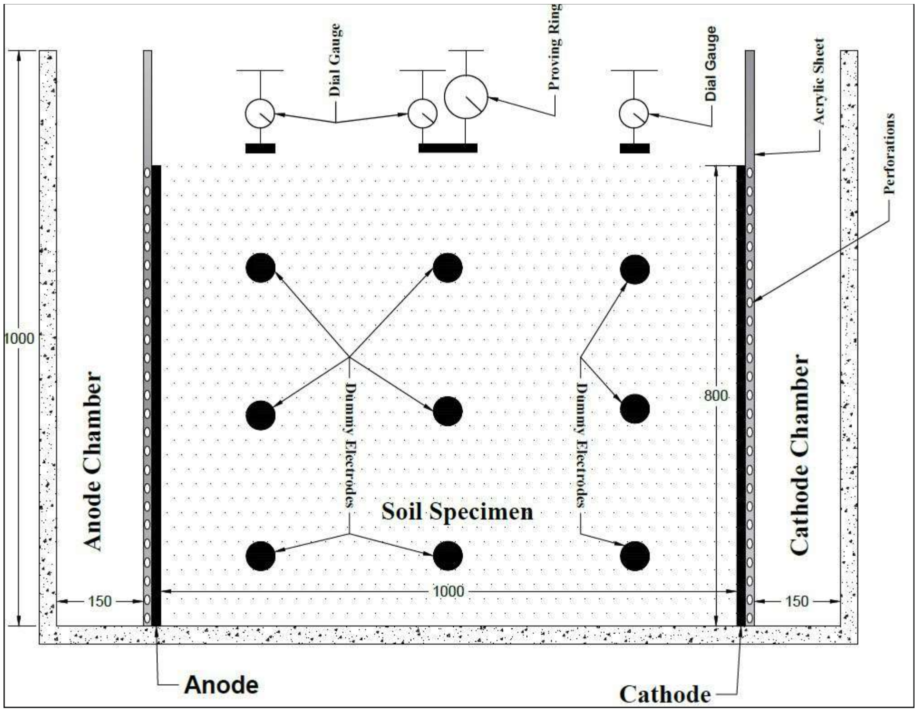

Figure 3.7: Elevation view of the rectangular electrokinetic model

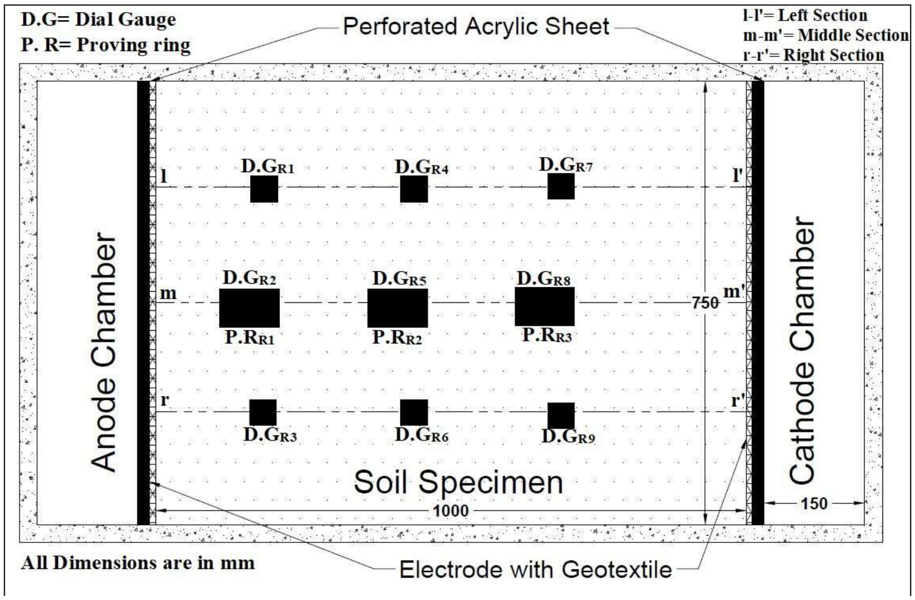

Figure 3.8: Plan view of the rectangular electrokinetic model

3.2.10.2 Circular Model Tank Equipped with ElectroKinetics

The large-scale circular electrokinetic model made with RCC is shown in Fig. 3.10 and Fig. 3.11 respectively. The anode, cathode, and soil chambers were in the form of three


(a) (b)

Figure 3.9: Rectangular EK model image (a) Soil chamber installed with dummy electrode (b) Soil chamber with dial gauge and proving ring

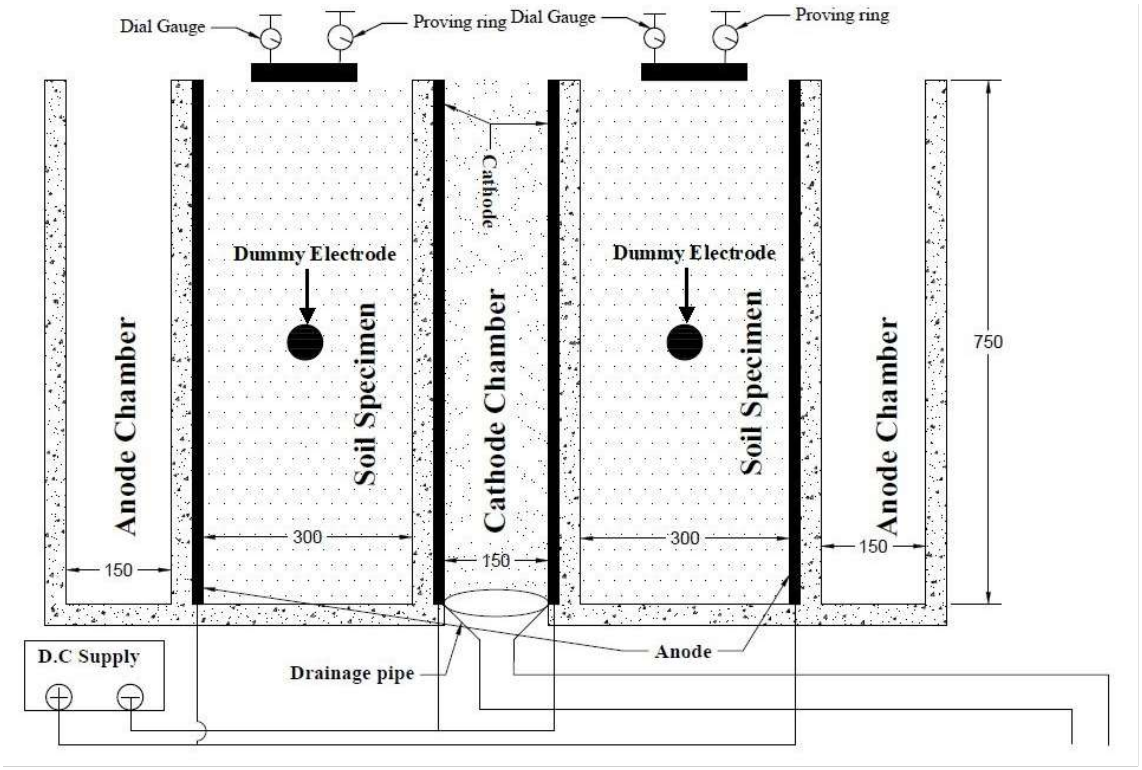

Figure 3.10: Elevation view of circular electrokinetic model

concentric compartments. The outermost chamber was the anode chamber. The middle compartment was for soil specimens, while the inner compartment was the cathode chamber. The diameter of the soil compartment and anode chamber was 600 mm and 150 mm, respectively, as shown in Fig. 3.11, while the height of the tank was 750 mm. The flow of the fluid was radially inwards from the anode chamber to the cathode chamber. Perforations were made on the walls of the anode chamber for the uniform flow of chemical solutions. Fig. 3.12a shows the image of circular EK model with a dummy electrode, dial gauge and proving ring. Four dial gauges and three proving rings were placed at the top surface of the soil for measuring the heaving and heaving pressure, respectively. It can be seen from Fig. 3.13, that the four dial gauges were placed at the mid-point of the anode and cathode. Furthermore, four voltage sensors and the four temperature sensors were placed at the mid-depth just below the four dial gauges to monitor the change in the voltage and temperature as shown in Fig. 3.12b. The cathode chamber was connected to a drain pipe at the bottom from where the electrolyte was drained out at regular intervals, while the anode chamber was refilled at regular intervals.

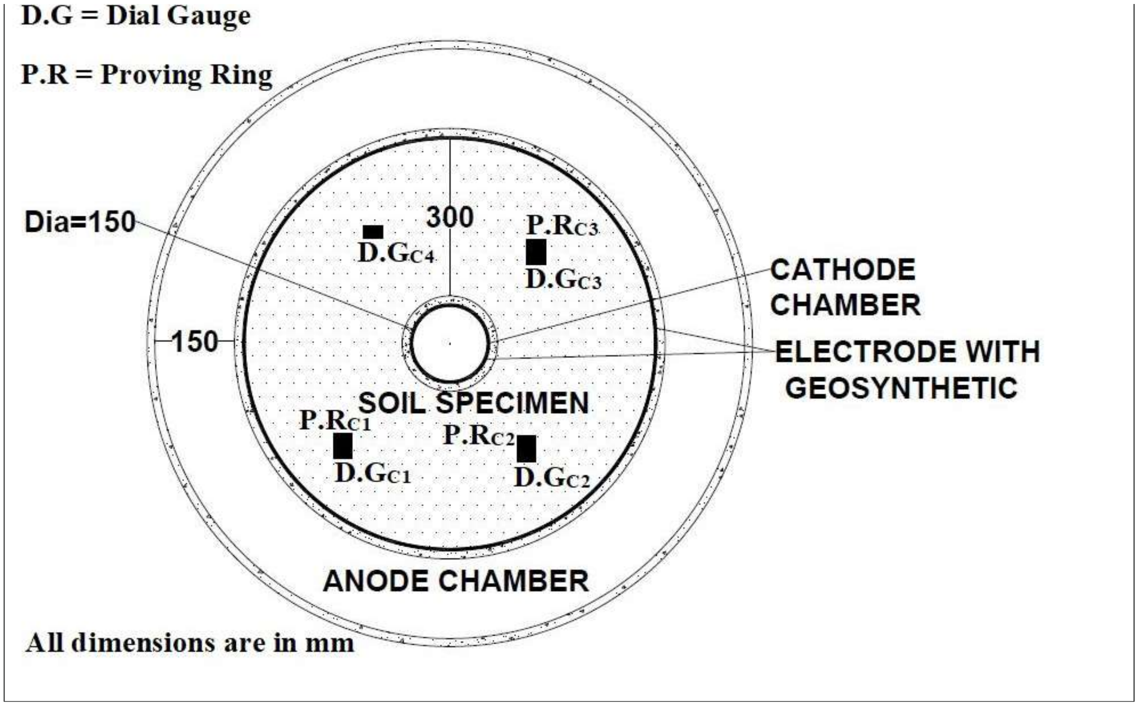

Figure 3.11: Plan View of Circular EK Model

3.2.10.3 Electrodes used in Large Scale Models

After the compaction of soil specimen in the large-scale model, a voltage gradient of 1V per cm is applied through electrodes. Brass net as shown in Fig. 3.14a was used as electrodes

(a) (b)

Figure 3.12: Circular EK model (a) soil chamber (b) soil with dummy electrode

Figure 3.13: Circular EK model soil with dial gauge and proving ring

for the application of voltage gradient through DC supplier as shown in Fig. 3.15 in this study. The main problem associated with the use of metal electrodes is rapid corrosion of electrodes due to electrochemical reaction that occurs during the electrokinetic process which reduces the efficiency of the electrokinetic technique. Recently, several studies have been done to use electrokinetic geosynthetic (EKG) electrodes to mitigate these problems and to increase the efficiency of the electrokinetic technique. In this, geotextile, as shown in Fig. 3.14b was used to prevent the direct contact of the electrode with soil. For this, a brass net wrapped between the geotextile shown in Fig. 3.14c is used in this study to delay the corrosion and increase the efficiency of electrokinetic treatment.

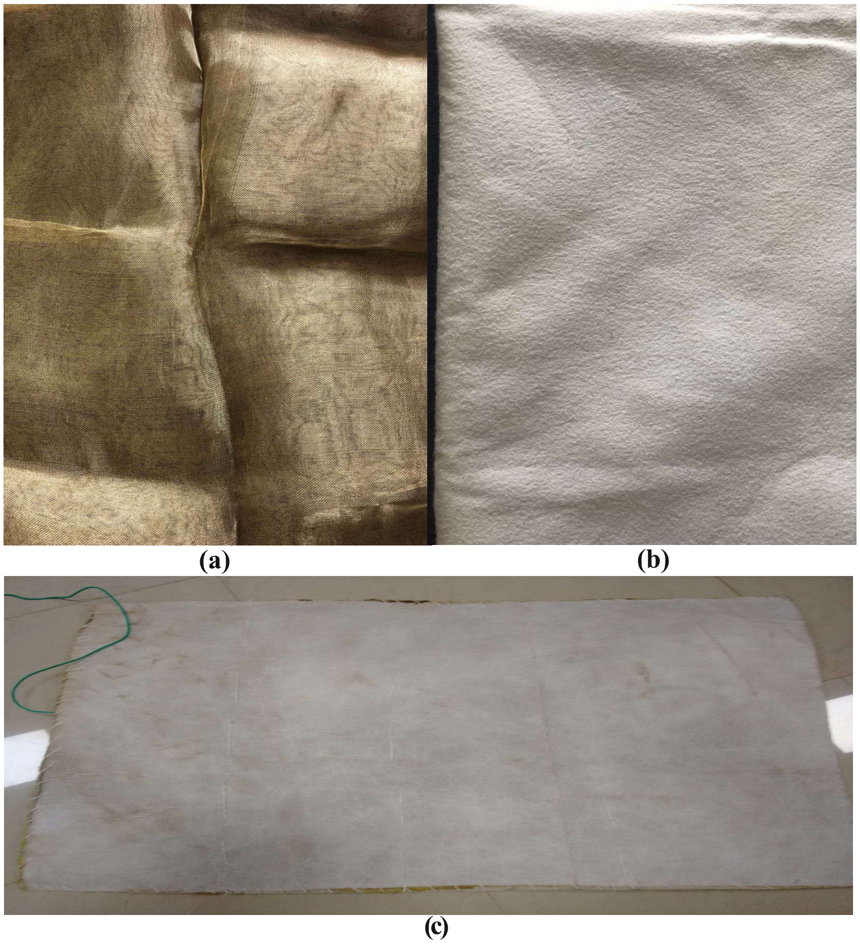

Figure 3.14: Electrode used in this study made of (a) brass net wrapped in (b) geotextile (c) EKG electrode

Figure 3.15: DC Supplier for the application of voltage gradient

3.2.10.4 Bench Scale ElectroKinetic Model

The main aim of the fabrication of a bench scale electrokinetic model is to analyse the applicability of chemical stabilizers for the treatment of alkali-interacted soil in the ground. The bench-scale EK set-up is made up of an acrylic hollow cylinder of length 60 cm and a diameter of 12 cm. The systematic diagram and image of the bench scale electrokinetic model are shown in Fig. 3.16 and Fig. 3.17 respectively.

The set-up consists of three chambers, namely anode chamber, cathode chamber and soil chamber. The anode and cathode chambers were 10 cm long positioned at both the ends of the soil chamber. The anode chamber is connected to a reservoir for filling the solution in the anode chamber at regular intervals. Three holes were made on the top of the soil chamber for inserting voltage probes. A hole was made in both the cathode and anode chamber to measure the pH of the solution during the test. A collecting chamber was placed at the cathode end to collect the excess fluid transported due to electroosmosis flow.

3.2.10.5 Electrodes used in Bench Scale Model

Two brass nets wrapped in geotextile acting as the electrodes are shown in Fig. 3.18a were placed along with the interface of soil and respective electrode chamber. Three dummy

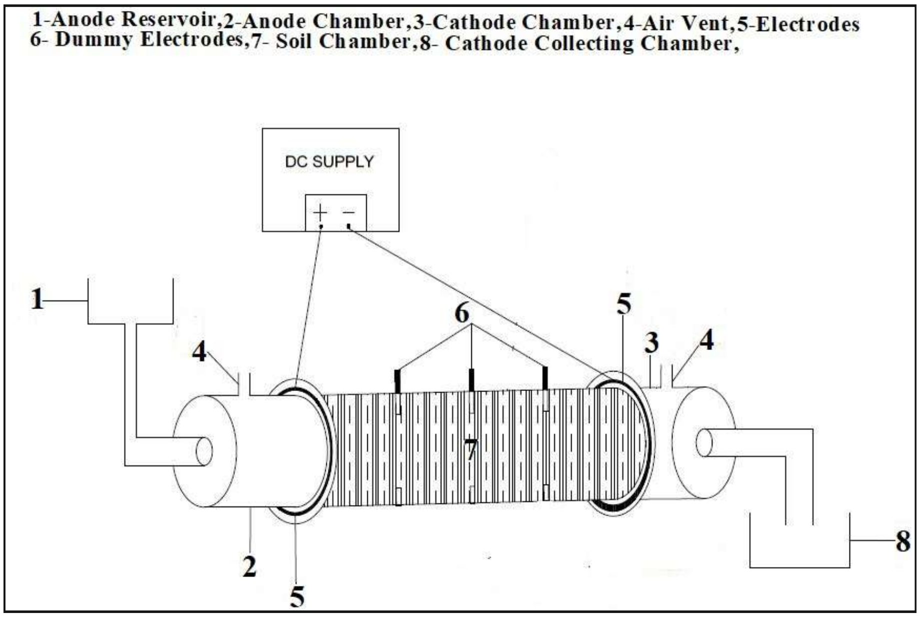

Figure 3.16: Schematic Diagram of bench scale electrokinetic model

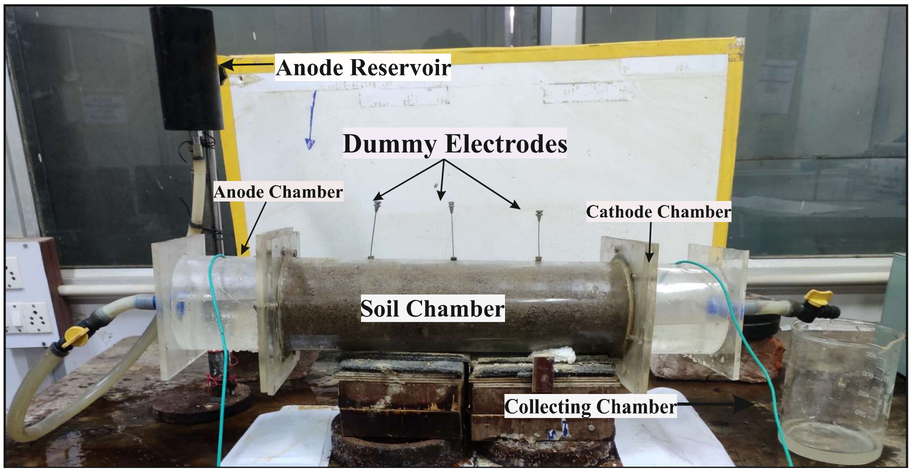

Figure 3.17: Bench scale electrokinetic model

electrodes were placed in the soil at a distance of 10, 20, and 30 cm from the anode to record the change in the voltage during the experiment.

3.2.10.6 Voltage Sensors

A voltage sensor was used to record voltage at three locations through dummy electrodes are shown in Fig. 3.18b. The specifications of the same are shown in Table 3.6.

Table 3.6: Specification of voltage sensor

Specification	Range
Operating Voltage	DC 4.5- 30 V
Measure Voltage	DC 0- 100V
Resolution	0.1 V

3.2.10.7 DC Supplier

The DC supplier used to apply voltage gradient is shown in Fig. 3.15. It has the maximum range of 0-200 V (least count 1 V) for voltage and 0-2 A (least count 0.01 A) for current. The DC voltage was applied across the electrode so that the flow would take place from anode to cathode.

3.2.10.8 Motorized Stirrer

The motorized stirrer as shown in Fig. 3.18c are used to stir the stabilizer slurry at regular interval to prevent the sedimentation of the solid particle in the electrolytic chamber.

3.3 Research Methodology Adopted

This section explains the research methodology and experimental procedure involved to fulfil the objectives highlighted in the present study. The methodology adopted in the present study is described step wise in the following Fig. 3.19. The research methodology aimed to analyze the influence of the nature and quantity of industrial waste and chemical stabilizers on the geotechnical properties of soil as well as on the engineering properties of alkali-interacted soil.

The whole experimental program was conducted in three phases. In the first phase, the effect of different molarities (8M, 12M and 16M) of NaOH solutions on the heaving and engineering properties of soil was evaluated. The most critical concentration of NaOH on the basis of these tests was selected. The heaving behaviour of soil in a large-scale electrokinetic model was studied on that NaOH concentration. In the second phase, a series of geotechnical tests on alkali interacted soil mixed with different percentages of industrial waste were executed to evaluate the efficiency of waste materials in stabilizing

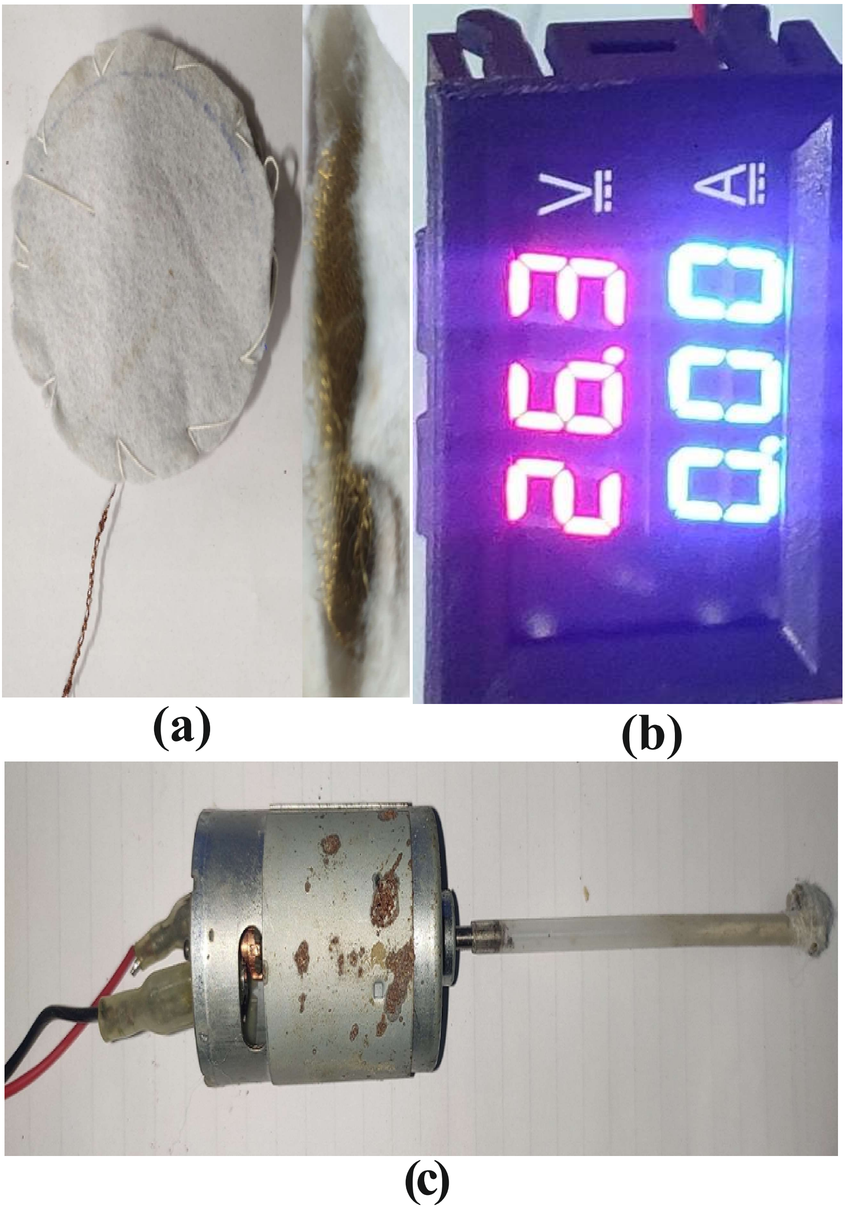

Figure 3.18: Image of (a) Electrode, (b)Voltage sensor, and (c) Motorized stirrer

the alkali interacted soil. In addition to this, the optimum dosage of waste material in controlling the alkali-induced heaving of soil was also evaluated. In the third phase, the effect of different chemical stabilizers in the treatment of alkali interacted soil was analysed. For this, the chemicals were injected into the soil using a bench scale electrokinetic model to simulate the field condition at the laboratory scale.

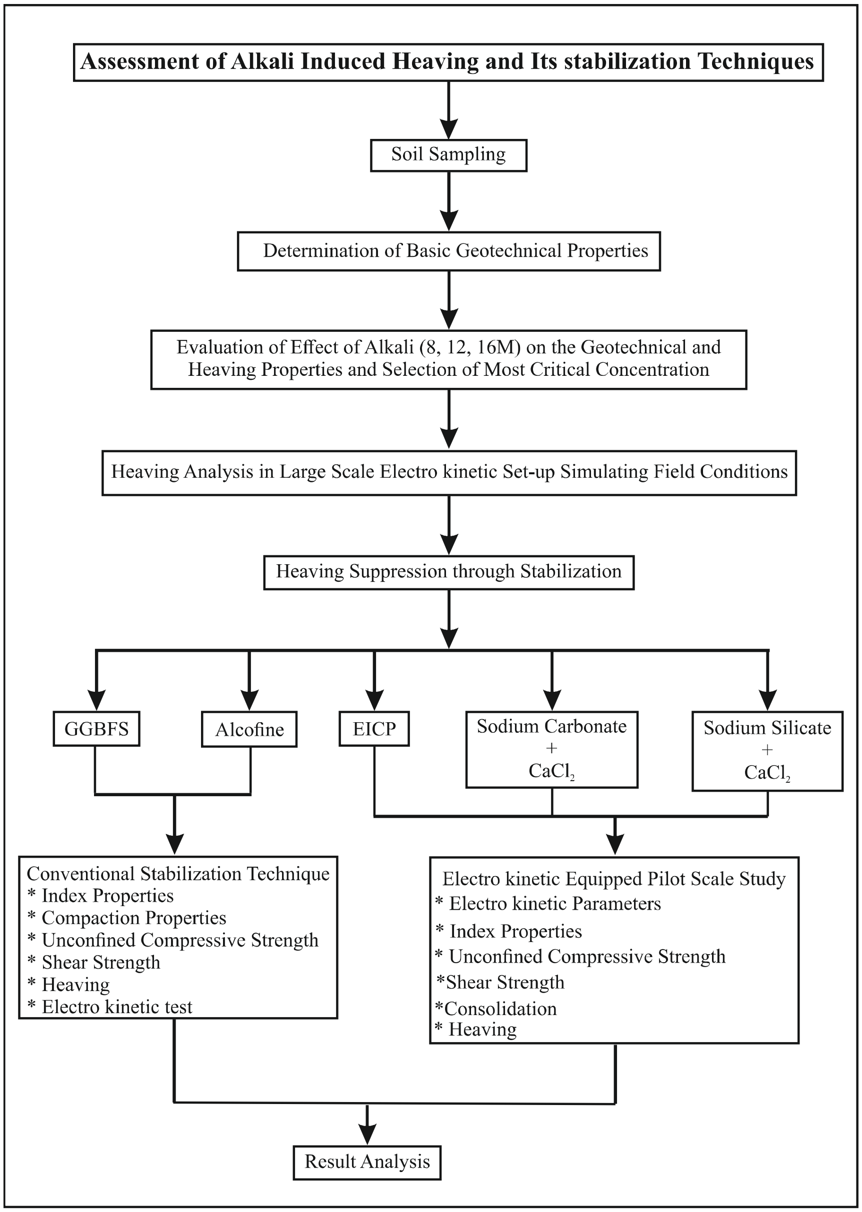

Figure 3.19: Flow chart showing methodology of the study

3.4 Summary

The chapter describes the details of materials along with their relevant properties in detail and also explained the proposed methodology adopted to achieve the objectives of the study. Their experimental setup, procedures and results have been discussed in detail in the subsequent chapters.