Chapter 2

Literature Review

2.1 General

Over the past few decades, various studies have been conducted to investigate and understand the effect of different concentrations of alkali solution on the heaving behaviour of different soils. Presently a few studies are available with regard to the effect of different concentrations of alkali on index and strength properties of different soils. This chapter provides a detailed literature survey on the percentage heaving in different soils along with the reason of heaving due to interaction with different concentrations of alkali solutions. The different heaving control techniques are also studied to understand the mechanism involved in controlling the alkali induced heaving using different additives. The research that involves the use of different stabilising techniques such as mechanical stabilization, chemical stabilization, bio chemical stabilization, and electrochemical stabilisation to improve the different properties including cohesion, angle of internal friction, bearing capacity, swelling potential, compressibility, hydraulic conductivity etc of soil are also reviewed.

2.2 Alkali-Induced Heaving

Alkali interaction can induce heaving in both expansive as well as non-expansive soils. The mechanism of heaving due to alkali interaction is different from the conventional heaving mechanism in expansive soils such as black cotton soils, bentonite that occurs mainly due to moisture variation. The interaction of alkali with soils leads to change in minerals of soil and the formation of new compounds, this kind of change in soil is responsible for heaving. Different case history of heaving in soil has been reported in many industries in which alkali has been used in production unit such as dyes, paper and pulp, aluminium and ceramic industries, etc. During transportation, unloading, storage, pumping of alkali solution, some amount of chemical spill out and seep into the ground which causes serious damage to soil as well the structure built on it. Several such incidents in different industries have been reported by different researchers (Hu et al., 2020; Kumar et al., 2019; Rao and Rao, 1994; Sibley and Vadgama, 1986; Sinha et al., 2003; Sivapullaiah et al., 2004; Sokolovich and Troitskii, 1976). The heaving in soil due to alkali interaction occurs mainly in two stages, in the first stage, the heaving occurs due to the accumulation of negative charges on soil particles, which causes repulsion of clay particles, and in the second stage the alteration in minerals of soil after alkali interaction which is responsible for larger swelling in samples. The alteration in soil structure has been observed after interaction with a very low concentration (0.1N) of alkali solution (Mitchell and Soga, 1993; Mulyukov, 2008), whereas the formation of a new compound was found at a high concentration of alkali solution (Chavali et al., 2017; Sivapullaiah et al., 2007). For decades, numerous investigations have been conducted on the effects of alkalis on clay minerals. Various laboratory examinations have been conducted to comprehend the influence of different concentrations of alkali solutions on different types of soils. The effect of three concentration of alkali solution (1N, 4N and 8N) on the heaving behaviour of black cotton soil was studied by Reddy et al. (2017), results obtained from the test conducted shows that the maximum heaving was observed as 54% in case of 1N alkali concentration as compared to heaving of about 30%, 19% and 12% due to inundation with 4N, 8N NaOH solution and water respectively. A significantly high-value heaving of about 36% with 4N NaOH was also observed in black cotton soil as compared to the heaving of about 3% with water (Reddy and Sivapullaiah, 2011). The addition of 1N and 2M NaOH solution induced a heaving of 17% and 25% as compared to inundation of water which shows heaving of about 2% (Sivapullaiah and Reddy, 2009; Sivapullaiah et al., 2010). Chavali et al. (2017) reveals the heaving behaviour of three kaolinitic group clays (red earth, ball clay and China clay) with four different concentration of alkali solution (0.1 N, 1 N, 4 N, 8 N), in this study the red earth, ball clay and China clayey soils shows the different magnitude of heaving depending upon the concentration of alkali solution.

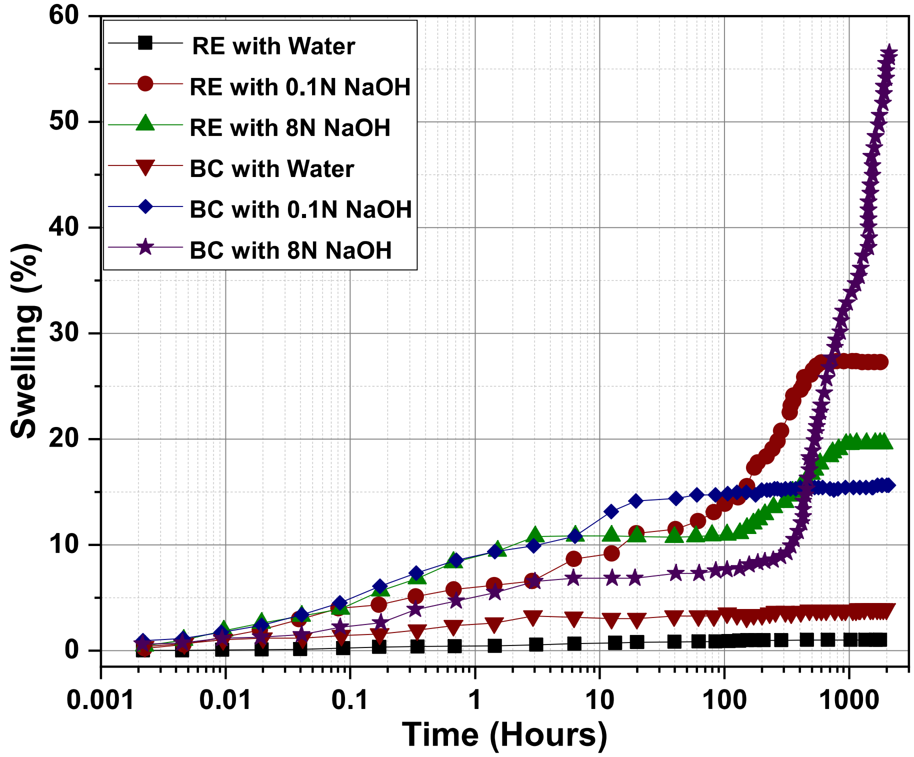

Figure 2.1: Percentage swelling in red earth and ball clay after inundation with different concentrations of alkali solution (Chavali et al., 2017).

The maximum and minimum magnitude of heaving in red earth (RE) was observed as 27 and 19% with 0.1N and 8N alkali solution respectively whereas the ball clay (BC) show maximum heaving 56% heaving with 8N and minimum heaving of about 15% with 0.1N respectively as shown in Fig.2.1. A similar result has also been obtained in the investigation conducted by Paulose et al. (2014); Sivapullaiah and Reddy (2009) in which the red earth shows the maximum heaving of about 27% and 17% with a concentration of 0.1N and 2M alkali solution.

2.3 Mineralogical Alterations in Alkali Interacted Soil

The mineral dissolution of clay minerals due to alkali interaction results in precipitation in soil. Numerous studies have been conducted to investigate the transformation of clay minerals due to alkali interaction (Bauer and Berger, 1998; Bauer and Velde, 1999; Cuadros and Linares, 1996; Taubald et al., 2000). On the basis of these studies, it can be summarised that the transformations of clay minerals are functions of the nature and chemical composition of the reacting alkaline solutions and those of the reacting minerals. The transformation of clay minerals with the formation of new minerals causes soil deformation, which eventually leads to structural failure. Hence, micro-level investigations play an important role in understanding the behaviour of soils. Sruthi et al. (2017) reported that the interaction of 4N NaOH solution leads to a change in the peaks of red earth with different volumes of alkali solution. They have reported no change in the peaks of uninteracted red soil has been observed when the quantity of alkali solution is less than 2.5 times the liquid limit of red earth. As the volume of alkali solution increases, a less intense peak of sodalite (sodium aluminium silicate hydroxide hydrate) has been observed, which basically belongs to the zeolite group of minerals. Similarly, an increase in the volume of interacting solution to 3.5–5 times the liquid limit resulted in the formation of a very intense peak of sodalite due to the higher dissolution of clay minerals, releasing alumina and silica. At 7 times liquid limit interaction, a very intense peak of sodalite and traces of topaz were observed. The reduction in the intensity of kaolinite peak and formation of the very intense peak of sodalite was also observed at a higher volume of interaction solution of 4N i.e., 10 times the liquid limit. Reddy and Sivapullaiah (2010) study suggested that soils containing interstratified minerals transform into zeolite P at lesser intensity alkali solution and sodalites at higher alkali concentrations whereas no significant mineralogical change in soil containing montmorillonite mineral has been observed. Reddy et al. (2017) show the formation of peaks of torana, tosudite, and sodalite in natural black cotton soil after interaction with 1N, 4N, and 8N alkali solutions. The reduction in peaks of saponite and increase in the peak of hydroxide as well as the transformation of saponite mineral into nontronite minerals has also been observed in black cotton soil after alkali interaction (Sivapullaiah et al., 2010). Sivapullaiah et al. (2005) have reported that the red earth soil and Kaolinite–alkali interaction shows new peaks of sodium aluminium silicate hydroxide hydrate (NASH) of very low intensity with 1N sodium hydroxide solution. The intensity of the peak of sodium aluminium silicate hydroxide hydrate (NASH) increases at 4 N hydroxide solution in both soils. The interaction of ball clay with 4N NaOH solution leads substantial reduction in the peak intensities of kaolinite and the formation of new peaks of sodalite and cancrinite. As the concentration of NaOH solution increased to 8N, all the peaks of sodalite disappeared and the number of cancrinite peaks increased. However, no change in the peak was observed at a lower concentration of NaOH solution.

Whereas in the case of China clay the new peak pertaining to sodalite has been observed with 1N NaOH solution and the intensity of the peak increases with an increase in the concentration of NaOH solution (Chavali et al., 2017).

2.4 Geotechnical Properties of Alkali Interacted Soil

Interaction of clay minerals with strong alkaline solutions causes mineralogical and morphological alterations in soils, which results in changes in the geotechnical properties of soil due to dissolution and precipitation of clay minerals. The interaction of alkali solution solubilizes the clay minerals, and these minerals reacted with other dissolved components leading to the formation of new compounds which precipitated again in the soil. The dissolution and precipitation of clay minerals occur simultaneously (Reddi and Inyang, 2000). The formation of a new compound alters the geotechnical properties. Sruthi et al. (2017) reveals that the liquid limit of red earth increases after interaction with 4N NaOH solution. Similar results have been observed by Sivapullaiah and Reddy (2009); Sivapullaiah et al. (2005) in which the liquid limit of red earth and black cotton soil increases after alkali interaction. The increase in liquid limit value with alkali interaction is mainly due to the increased pH value of soil after the accumulation of negative charge on clay particles which in turn increase in thickness of the diffuse double layer of clay particles (Mitchell and Soga, 1993). On the other hand, the reduction in liquid limit value with an increase in the concentration of alkali solution has been reported by Ramakrishnegowda et al. (2011); Soni and Varshney (2021). The reduction in liquid limit is due to the predominant influence of an increase in electrolyte concentration leads to a decrease in the thickness of the double layer of soil with less amount of clay. The addition of alkali solution in soil decreases its specific gravity value, the reduction in specific gravity is due to the less specific gravity value of sodium hydroxide solution as well as the specific value of the new compound formed (Ramakrishnegowda et al., 2011; Sivapullaiah et al., 2005). However, an increase in the specific gravity value of alkali-interacted soil has been reported by Soni and Varshney (2021) after alkali interaction. The change in compaction parameter of shedi soil and uncontaminated soil after alkali interaction was studied by Ramakrishnegowda et al. (2011); Soni and Varshney (2021).They reported the maximum dry density and optimum moisture content of soil increase in uncontaminated soil whereas the optimum moisture content increases and the maximum dry density decreases of shedi soil with the increase in the concentration of sodium hydroxide. The change in MDD and OMC value of soil is due to the flocculation of particles after alkali interaction. The decrease in shear strength and unconfined compressive strength of soil has also been observed after alkali interaction.

2.5 Heaving Suppression Technique

In order to control the heaving behaviour of soil under the effect of alkali solution a brief review on the use of different additives to suppress the alkali-induced heaving in the soil in a normal environment is summarized as follows:

2.5.1 Application of Salt Solutions

A laboratory investigation was carried out by Frydman et al. (1978) to understand the effect of potassium chloride on the heaving behaviour of clay. It has been observed that the addition of potassium chloride into the soil significantly reduces the heaving behaviour of soil. The reduction in the heaving of soil is mainly a result of this mineralogical change due to an increase in the concentration of electrolyte solution. The effect of 5% KCl and 5% $MgCl_2$ in controlling the alkali-induced heaving in black cotton soil has been studied by Reddy and Sivapullaiah (2011). The results show that the addition of these salt reduces the first stage of heaving and there is no subsequent effect on the second stage of swelling which occurs after mineralogical changes. Sivapullaiah and Hari Prasad Reddy (2010) describe the test results of the one-dimensional consolidation test which is carried out to assess the efficiency of potassium chloride solution in controlling the alkali (NaOH) induced heave in black cotton soil. The black cotton soil is mixed with 2% and 5% of salt solution and inundated with 4N of alkali solution. Similar results have been observed that the presence of potassium salt only controls the first stage of heaving due to potassium fixation. However, the second stage of heaving which occurs due to mineralogical alterations and due to the formation of zeolite minerals cannot be controlled with the use of potassium salt. An attempt has been made to investigate the effect of different concentrations of (1%, 3% and 5%) ferric chloride solution in controlling the heaving in red earth soil due to alkali interaction (Sivapullaiah et al., 2006). The results show that even 5% ferric chloride solution could not control the alkali-induced swell in kaolinitic soils as the formation of zeolite continues as the soil system remain highly alkaline in nature.

2.5.2 Application of Waste Materials

Sivapullaiah and Manju (2006) reported that even a small quantity of lime i.e 1% is adequate to control the heaving in soil contaminated with 4N solution, but 3% of lime is required to control heave in soil contaminated with liquor solution. The addition of Lime prevents the formation of zeolite which is responsible for heaving in soil resulting in a significant reduction in heaving. The formation of zeolite minerals is inhibited by the formation of a cementitious compound due to the pozzolanic reaction between soil and lime. The amount of Lime required to control the heaving depends upon the concentration of alkali solution.

Sivapullaiah and Reddy (2009) discussed the effect of different percentages of fly ash (25% and 50%) in controlling the heaving in red earth and black cotton soil due to 2M NaOH solution. The results show that heaving in black cotton soil reduces from 25% to 5% when mixed with 25% fly ash. No heaving occurs as the percentage of fly ash increases to 50%. Whereas in the case of red earth, the addition of 25% of fly ash reduces the heaving from 17% to 1% and with 50% fly ash the heaving becomes insignificant. The reduction in heaving in the presence of fly ash is due to a decrease in clay content after replacement and the formation of cementitious compound results from the pozzolanic reaction between soil and fly ash. These cementitious compounds inhibit the mineralogical change in the soil after interaction with 2M alkali solution. It was also found that the replacement of black cotton soil with 25% fly ash reduces the heaving from 17% to 4% on the inundation of 1N NaOH solution, and the heaving value reduced to 0.5% when the fly ash content increase to 50%. The heaving induced by 4N NaOH decreases from 25% to 8% on the addition of 25% fly ash and it goes on to decrease to 1.5% as the fly content increases to 50% (Sivapullaiah et al., 2008). Vindula and Chavali (2018) studied the effectiveness of fly ash in controlling the heaving in red earth, ball clay and China clay due to 4N NaOH solution. The results show that the heaving in red earth with 10, 20 and 30% of fly ash is about 21, 7 and 5% as compared to 22% with 4N NaOH solution. The maximum reduction in heaving of 77% was observed in the case of red earth mixed with 30% fly ash.

However, mixing 10% fly ash in ball clay and China clay effectively reduces the heaving from 44% to 10% and 22% to 1.5% respectively.

The efficacy of ground granulated blast furnace slag (GGBFS) in suppressing the alkali-induced heaving in red earth, ball clay and China clay was studied by Vindula et al. (2019). The experimental results show that the inclusion of 10% GGBFS showed a significant reduction in heaving compared to alkali contaminated soil. The heaving in red earth reduces to 9%, 6% and 5% on the incorporation of 10%, 20% and 30% GGBFS. Whereas the maximum reduction in heaving in ball clay and China clay from 44% to 14% and from 22% to 2% was observed on the inclusion of 20% and 10% GGBFS respectively. The high reduction in percentage heaving on the inclusion of GGBFS is mainly due to its cementitious nature. The sodium and calcium-based aluminium silicate hydrate gels were formed by the combination of rupture aluminosilicate clay nucleus and GGBFS with cations in the alkali solution. The development of calcium-based aluminium silicate hydrate gels resulted in reduced heaving due to its cementitious capabilities. The reduction in heaving in red earth on the addition of different parentage of fly ash and GGBFS are shown in Fig. 2.2.

2.6 Soil Stabilisation Technique

Soil stabilization is a method through which the geotechnical properties of the problematic soil gets improved. Soil stabilization has always been one of the major concerns in the field of geotechnical engineering. It became very crucial for the safe construction of a structure on weak soil strata. The stabilisation of soil can be achieved through various methods such as thermal, electrical, mechanical, chemical, and biochemical stabilization. The selection of stabilization techniques is mainly dependent upon the soil type and the property of soil to be improved. However, thermal and electrical methods are rarely used. The mechanical or chemical process by the use of additives has gained popularity because of their easy way to handle as well to manage in any construction environment. When the soil at any particular site does not possess desirable properties, e.g., appropriate cohesion, angle of internal friction, bearing capacity, swelling factor etc., it becomes necessary to improve these properties using any soil stabilization techniques. A brief review of different stabilization techniques to improve the geotechnical properties of problematic soils is

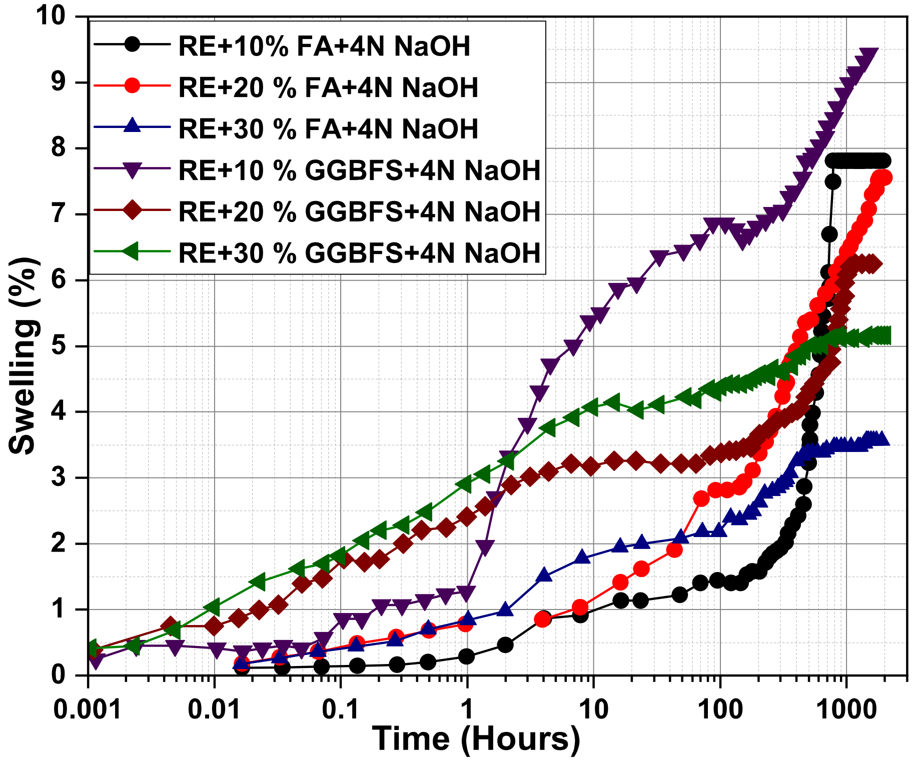

Figure 2.2: Use of Fly ash and GGBFS for the suppression of alkali induced heaving (Vindula et al., 2018; Vindula et al., 2019)

discussed below in detail.

2.6.1 Mechanical Stabilisation

Mechanical stabilisation is one of the most common and oldest techniques of ground improvement in which the density of soil is increased by the application of mechanical force and compacting of the surface layers by static and dynamic loading (Guetif et al., 2007; Patel, 2019). Mechanical compaction results in a reduction in voids of soil which improve the shear strength, permeability, compressibility and durability of soil. This method is most suitable for cohesionless soils in which mechanical compaction increases the interlocking of soil particles by rearrangement which results in an increase in strength as well as the reduction in settlement of soil. The main disadvantage of this method is that it is not suitable for the field condition in which the moisture fluctuation is very significant. The efficiency of this method may also decrease with the increase in clay content in the soil. The stabilization of soil is achieved by different means such as the use of stone columns (Al Saudi et al., 2016; Christoulas et al., 2000; Farouk and Shahien, 2013; Pivarč, 2011) , sand columns (Al Mosawe and Al Zuhairi, 2002; Al Saudi et al., 2016; Hussein, 2021; Prasad and Satyanarayana, 2021), soil nailing (Azzam and Basha, 2017; Benayoun et al., 2021; Mohamed et al., 2021) and so on.

2.6.2 Chemical Stabilisation

Chemical stabilisation is the oldest and most widespread technique in which various chemicals (organic and inorganic) are mixed in the soil to improve its desirable properties of soil. These chemical admixtures developed a cementitious and bonding action among the soil particles and between the soil and admixture which enhances the geotechnical characteristic of soil. For this different organic stabilisers like bitumen (Iqbal et al., 2020; Zumrawi and Awad, 2017), inorganic (pozzolanic) stabilisers such as lime (Abdi et al., 2020; Firoozi et al., 2015; Khemissa and Mahamedi, 2014; Parthiban et al., 2020; Szendefy, 2013), cement (Khemissa and Mahamedi, 2014; Parsons and Milburn, 2003; Ronoh et al., 2014; Shooshpasha and Shirvani, 2015), fly ash (Bose, 2012; Khan et al., 2022; Kumar and Harika, 2021; Nath et al., 2017; Radhakrishnan et al., 2014; Rupnow et al., 2015; Tastan et al., 2011; Yilmaz, 2015) , alccofine (Dutta and Yadav, 2021; Sambyal and Sharma, 2018; Saxena et al., 2018; Suresh and Murugaiyan, 2021b), ground granulated blast-furnace slag (GGBFS) (Kavak and Bilgen, 2016; Keramatikerman et al., 2016; Mujtaba et al., 2018; Rajak et al., 2020; Shariatmadari et al., 2021) etc. Some of these materials are industrial by-products or waste materials that possess cementitious properties. The handling and storage of huge production of these waste materials are major concerns. The main advantage of utilizing these materials not only solves these issues but also are cost-effective and give impressive results. The addition of these waste materials to the soil in the presence of water or alkali activator involves three basic mechanisms: cation exchange, flocculation and agglomeration, and Pozzolanic reaction, which leads to the formation of cementitious products that are composed primarily of calcium silicate hydrates or calcium aluminate hydrates, or both. Apart from these, some calcium-based chemicals, including sodium silicate, are used as chemical stabilisers. The application of these chemicals shows some long-term changes in geotechnical properties through the formation of strong chemical bonds that bind the soil particles and fill up the soil voids leading to an increase in the strength of the soil.

2.6.2.1 Stabilisation using Ground Granulated Blast-Furnace Slag (GGBFS)

GGBFS is one of the best replacements for cement and lime for the stabilisation of soil, as the production of cement and lime requires a large amount of energy and also a large amount of CO_2 and dust released into the environment during its production. GGBFS is a waste-by-product of steel industries which is produced after the quenching of blast furnace slag with water (Higgins, 2007) and the glassy granular materials with a similar appearance to sand is generated. The cementitious behaviour of these materials is excellent. They are grounded to the particle size similar to Portland cement and used as stabilizing material. After cooling, they are grounded to the fine particle similar to cement and used as stabilizing material due to its excellent cementitious properties. The physical properties and chemical composition of GGBFS depend upon the cooling process and raw materials used in the production of iron. GGBFS have outstanding engineering properties due to the presence of a high proportion of alumina (Al), silica (Si) and calcium (Ca). The improvement in geotechnical properties of soil through the addition of GGBFS is mainly attributed to the Physio-chemical reaction between the GGBFS and clay minerals leading to a reduction in plasticity and the pozzolanic reaction between soil and GGBFS. The addition of GGBFS to the soil alters the Atterberg's limits of the soil. Yadu and Tripathi (2013) studied the effect of the addition of different percentages of GGBFS on the soil. They observed that the liquid limit and plastic limit of soil decrease with increasing content of GGBFS which is similar to the observation reported by Estabragh et al. (2022); Mujtaba et al. (2018). The change in Atterberg limits is due to the non-plastic behaviour of GGBFS and the replacement of monovalent cations in the clay minerals by the divalent calcium ions. The decrement in liquid limit value can also be attributed to the reduction of the space between particles by increasing the degree of flocculation of the soil mass (Estabragh et al., 2022). The maximum dry density (MDD) value increase whereas the optimum moisture content (OMC) value decreases with the addition of GGBFS to the soil (Manjunath et al., 2011; Mujtaba et al., 2018; Sharma and Sivapullaiah, 2016).The increase in MDD value is due to the higher specific gravity value of GGBFS and the inclusion of GGBFS fills the voids in soils which results in an improvement in gradation of admixture. The reduction in OMC on the addition of GGBFS may be due to a reduction in plasticity and replacement of fines by GGBFS particles which reduces the surface area, hence the smaller surface area required less water (Al-Khafaji et al., 2017; Mujtaba et al., 2018). However, the opposite trend has been observed in the studies conducted by Kumar Sharma and Sivapullaiah (2012); Swamy et al. (2015) whose results show that the addition of GGBFS to the black cotton soil decreases both OMC and MDD values. The decrease in MDD value is due to the predominant effect of high frictional resistance offered by coarser GGBFS particles due to size and surface texture resisting the compactive effort effectively. The decrease in MDD may be also due to the utilization of compactive effort in breaking the bond between soil and GGBFS. It is well known that the cementitious property of GGBFS is governed by the presence of calcium ions. It has been observed that a pozzolanic reaction takes place between calcium ion of GGBFS and silica/alumina present in the clay minerals resulting in the formation of hydrate of Calcium Silicate and Calcium Aluminate. The chemical reaction that takes place between the ions is as shown in equations 2.1 and 2.2:

$$Ca(OH)_2 + SiO_2 \rightarrow CaO - SiO_2 - H_2O \tag{2.1}$$

$$Ca(OH)_2 + Al_2O_3 \rightarrow CaO - Al_2O_3 - H_2O \tag{2.2}$$

The formation of these pozzolanic/cementitious compounds depends upon the pH environment. The high pH of the soil increases the reactivity and solubility of ions which accelerate these reactions (Prusinski and Bhattacharja, 1999). Apart from these curing time and temperature also plays a vital role in pozzolanic reaction. The product of these reactions is deposited as a separate crystalline solid in voids of soil that binds soil particle together as well as surround the soil particles which in turn form a solid hardened skeleton. The formation of these bonds and changes in the structure of soil help to increase in strength and durability of soil as well as decrease the permeability and compressibility of soil. Nidzam and Kinuthia (2010) observed the formation of cementitious gel due to hydration of GGBFS which enhances the binding action between the soil particles which in turn increases the strength of GGBFS stabilized clayey soil. The gain in strength depends upon the curing period as well as the percentage of GGBFS. The test results show that the gain in strength in clay soil stabilised with 5% GGBFS after a 7-day curing period is greater than the strength of soil stabilised with 5% cement. The higher strength in GGBFS stabilised soil is due to the higher rate of hydration of GGBFS in the presence of an activator, which produces more crystalline cementitious products than the hydration product of cement. The rate of hydration of GGBFS with or without chemical activators is shown by Yi et al. (2014). The hydration of GGBFS alone occurs at a very slow rate and it increases with the use of activators such as lime, MgO, Sodium silicate, NaOH, and KOH (Abdullah et al., 2017; Al-Rkaby, 2019; Corrêa-Silva et al., 2020; Jin et al., 2015; Keramatikerman et al., 2016; Singhi et al., 2016; Swamy et al., 2015; Yi et al., 2015, 2014) etc. These activators create a pH environment due to which Si and Al minerals are easily dissolved. The release of these minerals undergoes a pozzolanic reaction with the charge-balancing interlayer cations Na^{2+} or Ca^{2+} which results in the accumulation and precipitation of sodium aluminosilicate hydrate (N-A-S-H) gel and calcium (alumino) silicate hydrate (C-A-S-H) gel as shown in the equation. The change in UCS value of soil after the addition of GGBFS into the soil are studied by different researchers (Al-Khafaji et al., 2017; Manjunath et al., 2011; Sharma and Sivapullaiah, 2016). Yi et al. (2015) documented the increase in UCS value of stabilized clay with different lime-GGBFS (l/g) ratios and with different curing periods. It has been observed that the (l/g) stabilized clay yields a higher UCS value than that of cement-GGBFS stabilized soil. The highest strength was achieved at (l/g) ratio of 0.2 and 0.10 for 7 days and 90 days curing period respectively. Similar trends of results have also been reported in the studies conducted by Keramatikerman et al. (2016); Padmaraj and Chandrakaran (2017); Sharma and Sivapullaiah (2016). The results show that even the addition of 2% lime to GGBFS can significantly improve the UCS value of soil. Estabragh et al. (2022) indicate the use of MgO as activators with GGBFS increases the strength of the soil. The increase in UCS value is a function of both MgO content and the curing period. The hydration of GGBFS occurs in the presence of MgO which leads to the production of cementitious gel which increases the strength of the soil. Corrêa-Silva et al. (2020) noted that the use of NaOH with GGBFS decreases the compressibility and increases the shear strength parameter of soil. The compression index and re-compression index value of soil stabilized with 7.5% GGBFS-NaOH reduces up to 58% and 83% after completion of the curing period of 28 days and 90 days respectively. The combination of GGBFS-NaOH behaves as the glue which binds the soil particle through the development of a cementitious bond. This also results in an increase in peak cohesion value from 71 kPa to 334 kPa and 503 kPa and the angle of internal friction increases from 7^o to 42^o to 49^o after 28 days and 90 days curing period. The improvement in geotechnical properties of soil with the addition of GGBFS is associated with increasing in the pH value of the solution due to the existence of calcium hydroxide which leads to the dissolution of silicates and aluminates originating from clay soil. These dissolved materials undergo a chemical reaction with calcium ions and produces additional cementitious materials. The produced materials such as CAH and CSH help to increase the strength of the soil (Estabragh et al., 2022). The pozzolanic properties of GGBFS also make it more suitable for the replacement of cement in concrete. The use of GGBFS in concrete improves the strength and durability of concrete (Bellum et al., 2019; Hutagi and Khadiranaikar, 2019).

2.6.2.2 Stabilization using Alccofine

Alccofine is ultrafine cementitious material which is a by-product during the fine grinding of iron slag produced in iron industries of high glass content that possess high cementitious properties (Reddy and Meena, 2017; Thangapandi et al., 2020). Based on the calcium silicate content the alccofine are categorised into two different groups, alccofine 1101 and alccofine 1200 series. Alccofine 1101 is microfine cementitious material with high calcium content which is used as a grouting material for rock and soil stabilization. Whereas, alccofine 1200 is the type of material that contains a low percentage of calcium silicate. Further, alccofine 1200 series are divided into 3 sub-group 1201, 1202 and 1203 depending upon the size of particles fine, microfine and ultrafine respectively (Gupta et al., 2013; Mathur and Mathur, 2018). The alccofine is manufactured in a controlled environment and the fine grinding is carried out by a control granulation process to achieve a fineness of 12000 cm^2/gm with unique chemistry (Jindal et al., 2017; Singhal et al., 2017, 2018; Srinath et al., 2021). The presence of a large percentage of CaO and ultra-fineness nature of alccofine which increases its hydraulic property, and pozzolanic reactivity makes its more suitable from all other admixtures such as silica fume, fly ash, GGBFS and etc (Gupta et al., 2013). The specific gravity, bulk density and average particle size varies from 2.5-3.0, 600-700 kg/cm^3, 4 to 6 µm respectively. It has been reported that the alccofine is mainly composed of SiO_2 (33-35%), Al_2O_3 (21-25%) and CaO (31-38%) with a glass content $\geq$ 90% (Srinath et al., 2021; Wanare et al., 2022). Alccofine provides Ca^{2+} which reacts with silica and alumina present in the soil to form a calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). The formation of these gel in the soil voids improves the packaging density of soil which improve the geotechnical properties of soil. Numerous investigations have been done to analyse the stabilizing effect of alccofine with or without admixture on the different types of soil (Abhijith et al., 2019; Dev and Sharma, 2017; Dutta et al., 2019; Rather et al., 2019; Suresh and Murugaiyan, 2021a). Dutta and Yadav (2021) conducted a series of experiments to investigate the impact of different percentages of alccofine on consistency limit, compaction and unconfined compressive strength of bentonite. The test results show that the inclusion of alccofine into the bentonite increases the liquid limit and plastic limit values. The change in liquid limit and plastic limit value on the addition of alccofine is due to the thickness of the diffused double layer and due to the cation exchange reaction, which causes the flocculation of soil which results in an increase in liquid limit and plastic limit value. However, the opposite trend has been observed by Dutta et al. (2019) which shows that the addition of alccofine into the bentonite soil decreases the liquid limit and plastic limit value. Shukla and Parihar (2016); Suresh and Murugaiyan (2021b) have also revealed similar results that the liquid limit and plastic value of black cotton soil decrease with the inclusion of alccofine. The reduction in this value was anticipated with the cation exchange and pozzolanic reaction due to the presence of CaO. These reactions not only affect the consistency limit but also cause the change in compaction value as well as the UCS value of soil. Several investigations have been carried out to assess the impact of alccofine on compaction parameters of different type of soil. According to Dutta and Yadav (2021) the MDD value of bentonite soil increases with the inclusion of alccofine. The increasing trend in MDD value was observed up to 8% of alccofine beyond this MDD value show decreasing trend. The experiment conducted on admixture of alccofine with bentonite and black cotton soil (Dutta et al., 2019; Shukla and Parihar, 2016; Suresh and Murugaiyan, 2021a) The presence of CaO promotes the base exchange reaction which leads to flocculation and agglomeration of mix and formation of cementitious compound which results in dense packaging. Further, the presence of fines fills the voids of soil which also increases the MDD value. The decrease in OMC value of alccofine is associated with the fine grinding of alccofine in the control granulation process to achieve a unique chemistry which requires a reduced water demand, leading to a reduction in OMC value of soil. The change in UCS value of different soil with alccofine are studied by many researchers. Dutta and Yadav (2021) conducted several UCS tests on bentonite with different percentages of alccofine and with different curing periods. It has been observed that the UCS value of soil increases with the incorporation of alccofine up to 8%. The increase in UCS value is also consistent with the increases in curing time. Further inclusion of alccofine decreases the UCS value of soil. The systematic increase in the UCS value of alccofine treated soil was reported by Dev and Sharma (2017); Godayal et al. (2018); Rather et al. (2019). Suresh and Murugaiyan (2021a) documented that the UCS value of black cotton soil increases with the incorporation of 3% and 6% of alccofine with 1% $CaCl_2$. as the percentage of alccofine increases from 6% the UCS value of soil reduces. The increase in UCS value of black cotton soil with the increase in the micro-fine slag content up to 6–7% but further inclusion of alccofine resulted in decrease in the strength of the soil (Shukla and Parihar, 2016). The improvement in the UCS value of soil is due to occurrence of pozzolanic reaction between the calcium ions present in the alccofine and Si or Al ions presents in the soil. The pozzolanic reaction results the development of cementitious gel in the voids of soil may have increases the packaging density and agglomeration of fine particle into large size particles, which in turn increases the UCS value of the soil matrix. The decrement in UCS value of soil inclusion of alccofine after reaching optimum value can be attribute to the presence of unreacted alccofine particles in the admixture which resulted in the formation of a weak cementitious bond. The swelling potential of black cotton soil with or without alccofine was also reported by Shukla and Parihar (2016); Suresh and Murugaiyan (2021a). The swelling of soil is reduced to half on addition of 6% of alccofine and further increases in alccofine completely eliminate the swelling behaiour. The angle of internal friction increases from 25.42^o to 38.83^o on the inclusion of only 3% alccofine in laterite soil (Abhijith et al., 2019). Wanare et al. (2022) uses alccofine as a grouting material to fill the cracks developed in marine clay in cured and uncured conditions, which affect the compressibility, stability, bearing capacity and settlement of soil. The efficiency of alccofine to improve cracking behaviour in marine clay test results has been represented in terms of crack and shrinkage intensity factor (CSIF). It has been observed that the CSIF value of stabilised soil during drying is reduced by up to 38% and up to 57% for uncured conditions. The test results also show that the alccofine content up to 10% is not effective in reducing the CSIF. The reduction in CSIF is due to the development of cementitious compounds after the pozzolanic reaction. Apart from these, several attempts have also been made to improve the properties of concrete, such as strength, durability, workability, and permeability, by using alccofine as a partial replacement for cement. The ultrafine nature and unique chemical composition of alccofine accelerate the hydration process and pozzolanic reaction. The inclusion of alccofnie resulted in good workability at low water content, reduction in segregation, reduction in heat of hydration, and reduction in permeability of concrete, and increased the rate of hydration process and improved the pozzolanic reaction to achieve high strength to concrete at the early curing stage. The improvement in the mechanical and durability properties of concrete has also been observed due to the presence of calcium (CaO) and silica (SiO_2) in alccofine (Sagar and Sivakumar, 2021; Srinath et al., 2021).

2.6.2.3 Stabilization using other Inorganic Chemicals

A number of eco-friendly and nontoxic silicate and calcium-based inorganic chemicals are also used for soil stabilization. These chemicals form a strong bond between the soil particles and also get precipitated in the form of an insoluble gel in the voids of soil which results in a hard soil skelton. It is well known that the use of different additives such as cement, lime, fly-ash, GGBFS etc, form calcium silicate hydrate as an end product after hydration reaction which is responsible for the increase in soil strength. Several researchers have done studies on the utilization of sodium silicate with different additives to improve the properties of soil (Fang et al., 2017; Gobinath et al., 2020; Hanegbi and Katra, 2020; Zhu et al., 2018). Hurley and Thornburn (1971) concluded that the ingression of sodium silicate with calcium chloride form an insoluble gel in the voids of soil. The sodium silicate reacts with the calcium ion forming a calcium silicate hydrate gel that binds soil or sediment particles together (Rafalko et al., 2007). Kazemian et al. (2011) identified the use of sodium silicate with cement shows promising results for the treatment of organic soft clay. The injection of sodium silicate with cement undergoes a chemical reaction that leads to the release of NaOH solution into pore solution. The release of NaOH increases the pH of the soil and accelerates the formation of CSH gel which results in increasing the strength of the soil (Suganya and Sivapullaiah, 2016). The use of NaOH with sodium silicate results in the formation of additional Calcium Silicate Hydrate (CSH) with amorphous gel. whereas the use of sodium silicate solution alone resulted in mainly amorphous products with only a small quantity of crystalline CSH (Phoo-ngernkham et al., 2015). The mechanical properties of fly ash and Portland-based geopolymer were improved with the use of NaOH along with sodium silicate as an activator (Phoo-Ngernkham et al., 2017). Due to the high solubility of sodium silicate, it can be beneficially used for grouting.

Hossein et al. (2012) use the sodium silicate solution as a grouting material for enhancing the shear strength of organic soil. Kazemian et al. (2011) investigated the effect of sodium silicate with cement and calcium chloride for the stabilization of soil through the grouting process. Zhu et al. (2018) conducted a comparative study on the grouting effect of cement with and without sodium silicate. It has been observed that the grouting quality of cement-sodium silicate slurry is better than that of cement slurry. The laboratory results show that the setting time of cement-sodium silicate slurry is less than that in the practical grouting environment where the grout slurry solidifies in soil. The viscosity of sodium silicate and cement solution was analysed by Sina et al. (2010). The test results show that the viscosity of grout increases with the ratio of cement and sodium silicate. The increase in viscosity was attributed to the formation of the polymerised gel after the rapid reaction between cement and sodium silicate. Li et al. (2017) modified the compressive strength of Portland cement using sodium silicate. Cong et al. (2014) while working on soft clay concluded that the addition of sodium silicate can significantly improve the mechanical properties of soil. It is found that maximum improvement in compressive strength is achieved at 2% sodium silicate. Ma et al. (2015) also deduced a similar trend in which the unconfined compressive strength of cement mixed with clay on the addition of sodium silicate and with the curing period. Gobinath et al. (2020) conducted a series of geotechnical on gravely soil with sodium silicate (1%) and different banana fibres (0.1, 0.2,0.3,0.4,0.5%). The addition of 1% sodium silicate with 0.5% banana fibre increases the UCS value of the soil by 445%, shear strength by 80% and CBR value by 1083% respectively. Reddy et al. (2015) investigated the swelling behaviour of expansive soil on the different percentages of $CaCl_2$ and sodium silicate. The test demonstrates that these chemicals exhibit better performance on swelling characteristics. Adlin Rose et al. (2021) observed that different percentages of sodium silicate (2,4,6,10,15 and 20%) could apply to stabilise the contaminated soil which can affect public health on disposal. The test result shows the increase in shear strength and CBR value of contaminated soil with sodium silicate.

One of the important calcium compounds is $CaCl_2$, which is also used as a soil stabiliser. The use of $CaCl_2$ with or without any additives improves the geotechnical properties of soil. The main advantages of the use of $CaCl_2$ are that it improves the strength and durability of soil; reduces the compressibility of soil; makes the soil waterproof; reduces construction costs; and many more (Solanki and Zaman, 2012). Ramana Murty and Hari Krishna (2007) studied the use of $CaCl_2$ in place of lime for improvement in slopes made of expansive soil. The addition of $CaCl_2$ reduces the liquid limit as well as the swelling of expansive soil. The use of 1% of $CaCl_2$ with kaolinite as a grout increases the shear strength of the grout material after the ion exchange and pozzolanic reaction between calcium ion and kaolinite. Similar results have also been reported by Zumrawi and Eltayeb (2016) that the addition of different percentages of $CaCl_2$ (0,2,5,10,15%) increases the UCS value of soil and reduces the swelling behaviour of expansive soil. Krishna and Ramesh (2012) investigated the strength behaviour of black cotton soil with $CaCl_2$. The test results show that the bearing capacity of black cotton soil increases from 1360 kPa to 5198 kPa with the addition of 3% $CaCl_2$. The addition of $CaCl_2$ initiates the clustering effect of sol which leads to an increase in the shear strength of the soil. Suresh and Murugaiyan (2021b) studied the microstructural change in the expansive soil after stabilized with different percentages of $CaCl_2$ and alccofine. The combined effect of fly ash and $CaCl_2$ on the pavement base course and subgrade was investigated by Shon et al. (2010). The test results show that the addition of $CaCl_2$ into fly ash significantly increases the early and long-term strength of base materials of pavement. The ingression of NaOH followed by $CaCl_2$ leads to calcite precipitation in the voids of soil after the cementation reaction between calcium ion and silica ion in the presence of NaOH. Due to the good solubility of these chemicals, they can be used to improve the foundation soil in the field (Thyagaraj et al., 2012). Other chemical sodium carbonate can also be used for improving the geotechnical properties of soil. Limited research has been done to utilize sodium carbonate for the stabilization of soil. Nayak and Singh (2017)studied the effect of sodium carbonate on the CBR value of expansive soil. The CBR value is improved by 38.46% with the addition of 1% sodium carbonate. The stabilization of black cotton soil with sodium carbonate is also investigated by Ramesh et al. (2012). It was observed that only the addition of 2% of sodium carbonate effectively reduces the swelling potential of soil and the maximum UCS value is achieved at 0.5% of sodium carbonate. A similar investigation is also carried out by Shaik Basheer (2017). It was found that the shear strength parameter of soil increases with 1.5% of sodium carbonate. The addition of 3% of sodium carbonate could effectively reduce the differential free swell index. Several investigations were also carried out to produce the precipitation of calcium carbonate in the voids of soil using sodium carbonate and calcium chloride. Han et al. (2021) conducted different series of experiments to improve the geotechnical properties of expansive soil using different percentages of calcium chloride and sodium carbonate. The experimental results show that the mixing of 21.2% sodium carbonate with 27.5% calcium chloride in the soil reduces the swelling from 56% to 32%. The swelling value of expansive soil reduces to 27% with the addition of 27.5% calcium chloride followed by 21.2% sodium carbonate. The UCS value and shear strength parameter of expansive soil also increase with the addition of sodium carbonate and calcium chloride. Kirboga et al. (2014) investigated the morphological properties of calcium carbonate through sonications after precipitation in the voids of soil using sodium carbonate and calcium chloride.

2.7 Stabilization of Soil using Bio-Chemicals

The use of bio-chemical also provides an alternative and effective method for soil stabilization. Soil stabilization using the bio-chemical method is achieved either by Microbiologically induced calcite precipitation (MICP) and Enzyme-induced calcite precipitation (EICP). The main mechanism involved in the MICP technique is the utilization of microorganisms and enzymes for the precipitation of $CaCO_3$. In MICP technique involves the utilization of different types of microorganisms such as Sporosarcina pasteurii, Idiomarina insulisalsae, Proteus vulgaris, Proteus mirabilis, Helicobacter pylori, and Ureplasmas (Mocllicutes) etc. for the precipitation of $CaCO_3$ precipitation (Umar et al., 2016). The main disadvantage of this technique is that these microorganism yields maximum $CaCO_3$ in highly control environment condition. To eliminate the challenges in the handling of these bacteria, an alternative solution is the use of ureases (enzymes) with urea and calcium chloride for the precipitation of $CaCO_3$ (Carmona et al., 2016; DeJong et al., 2010). The urease enzyme used in the EICP process is extracted from different plants such as jack beans, pigeopea, melon, squash, plants of the different pine families and some other beans (Das et al., 2002). The urease enzyme used for hydrolysis of urea produces ammonia and carbonate ions which raise the pH of the solution. The carbonate ions react with calcium ions leading to the formation of $CaCO_3$ crystal. The chemical equation involved in this process are shown in equations (2.3) and (2.4):

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + CO_3^{2-} \tag{2.3}$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3(precipitate) \tag{2.4}$$

Soil stabilization through $CaCO_3$ precipitation is achieved either by bio-clogging (deposition of $CaCO_3$ in voids of soil) or bio-cementation (increases the bond strength of soil particle which enhance the strength of soil) (Ivanov and Chu, 2008). The efficiency of bio-clogging depends upon the size of $CaCO_3$ and voids space of soil. The change in soil properties such as strength, compressibility, permeability, swelling potential and volume change properties depends upon the amount of $CaCO_3$ precipitation. The quantity of $CaCO_3$ precipitation in the EICP process is dictated by the quantity and ratio of $CaCl_2$, urea and enzyme used (Almajed et al., 2018). Any change in molarity and proportion of these chemicals may increase or decrease the $CaCO_3$ precipitation. The rate of urea hydrolysis is mostly affected by the amount of enzyme used. For a given amount of enzyme, an increase in urea-$CaCl_2$ proportion decreases the efficiency of $CaCO_3$ precipitation because the higher concentration of urea-$CaCl_2$ acts as a limiting reagent which hinders the catalysing capacity of the urease enzyme. At low urea-$CaCl_2$ concentration, the unreactive enzyme significantly decreases the hydrolysis process of urea which results in a decrease in $CaCO_3$ precipitation (Chandra and Ravi, 2021). Apart from these, the EICP process is also affected by the pH environment and temperature (Ahenkorah et al., 2021). Numerous attempts have been made to correlate the proportion of different chemicals used in the EICP process.

Lee and Kim (2020) conducted a comparison study on the $CaCO_3$ precipitation ratio through two different techniques: EICP (using yellow soybean) and MICP (using ureolytic bacteria) for the hydrolysis of urea. The tube precipitation test is carried out to determine the $CaCO_3$ content using MICP and EICP techniques. The test results show that EICP is a good alternative to MICP. The increase in the UCS test is expressed in the ratio of treated and untreated soil. The UCS value of soil increased up to 2.72 after being EICP treated. Neupane et al. (2013) use the different concentrations of urea, and calcium salt along with a fixed amount of urease enzyme as a grout material to evaluate the optimum precipitation ratio of $CaCO_3$. The quantity of all three chemicals corresponding to the optimum value of precipitation ratio of $CaCO_3$ is grouted into sand samples compacted in PVC cylinders. The test was carried out on both small and large scales. It was found that even a small amount of enzyme (2g/l) yields a precipitation ratio up to 80%. A similar technique has also been employed by Yasuhara et al. (2012) to improve the compressive strength and permeability of sand. The compressive strength of sand varies from 400 kPa to 1.6 MPa whereas the permeability of sand reduces by one order as compared to the initial value. The improvement in mechanical properties of sandy soil is observed after calcite precipitation. The improvement in UCS value of three different soils (silty sands, clayey sand and silt) in the mixing of EICP solution was investigated by Chandra and Ravi (2021). The urease enzyme used in this experiment were extracted from agricultural sources for $CaCO_3$ precipitation. The optimum value of urea-$CaCl_2$ and urease solution obtained from the beaker experiment is mixed with all three types of soil to prepare a UCS sample of soil. The results show that the improvement in UCS value of silty sand (SM) and clayey sand (SC) is more as compared to silt. A bucket test was conducted to analyse the efficiency of the calcium carbonate column prepared from the injection of EICP solution through a small size pipe into the soil. This EICP soil column acts as soil nails which improve the strength and stiffness of soil (Kavazanjian Jr et al., 2017). Putra et al. (2016) used magnesium chloride with calcium chloride in EICP solution to enhance the production of carbonate precipitation. $MgCl_2$ acts as a delaying agent which reduces the rate of precipitation, thus increasing higher productivity. A small quantity of $MgCl_2$ increases the productivity of precipitation ratio up to 90%. The presence of Mg^{2+} reduces the size of precipitation crystal which results in agglomeration of carbonate. The relative higher improvement in UCS value of treated soil of about 0.6 MPa was obtained with the addition of $MgCl_2$. A similar experiment has been carried out by Almajed et al. (2019). They use the non-fat milk powder in EICP solution to increase the size and amount of $CaCO_3$ precipitation in the soil which enhances the compressive strength. Oliveira et al. (2017) studied the efficiency of calcite precipitation in a different type of soil through the enzyme. The strength of sandy and silty soil increases up to 106%. Whereas, a reduction in strength and stiffness in organic soil up to 50% was also observed. Almajed et al. (2020) comparison of the UCS value of sand treated with cement, lime, and EICP. The highest UCS value of sand was found in the case of EICP-treated sand as compared to treatment with cement and lime. The UCS value of sand increased to 700 kPa treated with EICP, whereas it was 438 kPa with 8% cement and 8% lime. Putra et al. (2018) studied the evolution in the shear strength parameter of sandy soil after the application of enzyme-mediated calcite precipitation (EMCP). The cohesion value of sandy soil increases up to 53 kPa after 4.1% precipitation of calcite. Moghal et al. (2020) conducted a series of experiments to restrict the movement of heavy metals in soil using the EICP technique.

2.8 Electrokinetic (EK) Technique

EK technique is defined as the migration of ions, physicochemical action of charge particle and effect of applied voltage for fluid transport in porous media. The EK technique involves electroosmosis, electrophoresis, streaming potential and sedimentation potential (Mitchell et al., 2005). Apart from these, one of the major phenomena is electromigration which occurs in soil under the application of an electric field (Yeung, 2006). Out of this electroosmosis, electromigration and electrophoresis are most important in the field of geotechnical engineering due to their practical application for the transportation of charged particles and water in fine-grained soil. Electroosmosis is defined as the movement of fluid from one end to another end of the soil specimen placed between the electrodes under a voltage gradient. This phenomenon occurs mainly in clayey soil containing the presence of charged ions. The electroosmosis flow velocity in the soil given by Azzam and Oey (2001) are shown in equation 2.5;

$$V_e = K_e i_e \tag{2.5}$$

where, V_e = the electroosmotic flow velocity, k_e = the electroosmotic permeability coefficient, ie = the electrical potential gradient $\Delta U/l$, U = the electrical potential, l = is the length of soil specimen.

The movement of charged ions towards their opposite electrode in the pore fluid due to electrostatic attraction is known as electromigration. The positive ions move towards the cathode and negative ions move towards the anode under the effect of a direct current across the soil specimen. The mass flux is the function of the electric voltage gradient, ionic mobility and concentration of ions. The mass flux per unit cross-section was given by Azzam and Oey (2001) is shown in equation (2.6),

$$J_{ems} = ui^* i_e c_i \tag{2.6}$$

Where, ui^* = effective ionic mobility, i_e = is the electrical potential gradient $\Delta U/l$, c_i = concentration of ions.

Whereas, the transport of the larger colloid or other charged material in the soil specimen is termed electrophoresis. In this phenomenon, the negatively charged particle

is attracted electrostatically to the anode and they are repelled from the cathode. This phenomenon become more important in EK remediation of contaminated soil through surfactant. This technique is applied to the soil containing charge contaminant or high-water content clays such as mine waste, bentonite clays and etc (Acar and Alshawabkeh, 1993). Apart from this phenomenon, two other mechanisms electrolysis of water and the reaction of electrodes also affect the EK method which also occurs after the supply of voltage gradient through electrodes. In electrolysis oxidation and reduction of water occurs under voltage gradient. The oxidation of water occurs at the anode as shown in equation (2.7) which leads to the formation of oxygen and reduction occurs at the cathode as shown in equation (2.8) which leads to the release of hydrogen. The chemical equation involved in the electrolysis is given as:
At Anode:

$$2H_2O - 4e^- \rightarrow O_2 + 4H^+ \tag{2.7}$$

At Cathode:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \tag{2.8}$$

The electrolysis of water generates an acid front at the anode and a base front at the cathode. The reduction in pH at the anode was observed due to the migration of the hydrogen ions towards the cathode. Whereas, the migration of hydroxide ions from the cathode to the cathode leads to an increase in pH value near the cathode (Barker et al., 2004). These fronts meet in the soil specimen during migration towards each other. The variation in pH at electrodes and the development of pH gradient across the soil sample influence the solubility of the electrolytes.

An electrochemical reaction occurs at the electrode surface after interaction with fluid during the application of electric current through these electrodes. This electrochemical reaction is known as an electrode reaction. The oxidation reaction at the anode and reduction reaction occurs at the cathode (Liaki, 2006). This reaction depends upon the electrode materials and properties of fluids (Barker et al., 2004). After these reactions, electrons changes from metallic phase to electrolyte phase in solution. High pH value and oxidation reaction at the anode causes rapid corrosion of electrodes made of metals. The chemical reaction involved in the corrosion process is shown in equation (2.9):

$$Me \rightarrow Me^{n+} + ne^- \tag{2.9}$$

Where M_e refers to M as metal and e^- as electrons.

The metal ions produced in the EK process migrate into the soil, which acts as a cementing agent and enhances the strength of the soil. The metallic cations combine with the hydroxide ions and get deposited in the voids of soil in the form of metal hydroxide, which forms strong interparticle bonds. To prevent the decaying of electrodes due to corrosion and increase the efficiency of the EK technique inert polymers were used to cover the metals and conducting wire (Azhar et al., 2018; Bourgès-Gastaud et al., 2017; Glendinning et al., 2007). Apart from these, geotextiles have also been used to warp the metal electrode to prevent direct contact of the electrode with fluid (Hu et al., 2016; Jian et al., 2019; Zhuang et al., 2013).

Several studies have been conducted to investigate the application of the EK technique in the fields of geotechnical engineering. Most of the research shows impressive results on the useful implications of the EK technique. One of the main applications of EK is the rapid dewatering of low permeable soil. The rapid dewatering also causes a more effective and fast consolidation process of compressible soil. The removal of excess water from the voids of soil leads to a change in soil structure, which results in the higher strength and stability of the soil. The application of the EK technique acts similarly to that of preloading, which is used for the consolidation and improvement of soft soil. The main advantage of using EK consolidation instead of preloading is that it accelerates the consolidation process, especially in low permeable soil. In early 1930, Casagrande used the EK technique for the first time in the field of geotechnical engineering for rapid dewatering of low permeable soil (Ou et al., 2009). The result shows a larger reduction in water content results in an increase in the shear strength of the soil. After that several attempts have been made to utilize the EK technique for improving the properties of low permeable soil. Some of them are summarized in Table 2.1.

Later in the 1980s, the EK technique have also been used for the remediation of different types of contaminated soil. Most of the applications since then were based on laboratory data and only a few papers describe in-situ applications. The efficiency of certain heavy metals in electrokinetic remediation is dependent on the mineralogy and composition of treated soils. The extraction of heavy metal from the contaminated soil using electrokinetic is carried out by electrical adsorption. As the electric voltage gradient is developed between the contaminated soil through electrodes, the positive charge metal

Table 2.1: Electrokinetic enhanced technique for rapid consolidation of low permeable soil.

Authors	Soil type	Applied voltage or current	Electrode type	Remarks
Zhuang et al. (2013)	Sludge field	290A for 10 days 50V for 1 day 80V for 9 days	Electro-Kinetic Geosynthetics (EKG)	Corrosion-proof EKG was developed from electric conductive polymers with two copper wires. After application of DC current reduces the water content of sludge from 62% to 36% in 36 days and improved the bearing capacity from negligible to 70kPa.
Jian et al. (2019)	Hangzhou Silt	30-15V	Copper, iron and stainless steel wrapped in geotextile	The electro-osmosis technique is considered to be inapplicable for soils with water content less than 70%,salinity higher than 2%, or humus content higher than 20%.

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Table 2.1 – continued from previous page

Authors	Soil type	Applied voltage or current	Electrode type	Remarks
Rittirong et al. (2008)	Calcareous sand	6V and 13V with polarity reversal after 72h and 120h from the start of test.	Stainless steel	The electrokinetic treatment generated significant iron-rich cement and increased the pull-out resistance of the caissons by over 90%.
Azhar et al. (2018)	Soft highly Compressibility clay	50V per cm	Specially made of inert material of electrokinetic geosynthetic	After the application of voltage gradient, the water content of soil gets reduced significantly.
Hu et al. (2016)	Soft kaolinite soil	20V	Iron bars Iron wires wrapped in geotextile	The crack formation was restrained with the application of deep electro-osmotic consolidation (DEC) technique, and therefore the drainage and consolidation effect were improved.

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Table 2.1 – continued from previous page

Authors	Soil type	Applied voltage or current	Electrode type	Remarks
Ukleja (2020)	Cohesive soil	24V and 3A	Flat steel bars	The electrokinetic method diminishes the water content in the soil by approximately 4.6% within two weeks. Although the vacuum method demonstrates ability to dewater the soil comparable to the gravitational outflow, it is far less effective than the electrokinetic method.

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Table 2.1 – continued from previous page

Authors	Soil type	Applied voltage or current	Electrode type	Remarks
Fu et al. (2019)	Clay slurry	0.5V per cm -1V per cm	Iron plates	The volume of evaporated water and electrolytic water increased with increasing voltage gradients; however, a voltage gradient greater than 1.0V/cm had no significant effect on evaporation.
Bourgès-Gastaud et al. (2017)	Oil sand tailings	12V	eGCPs which is composed of a substrate, a geomembrane, and numerous wires.	A significant improvement of the shear strength from nearly 0 kPa to a mean value of 25 kPa was obtained and the final solids content in that case was about 70%,starting from an initial solids content of 45%.

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Table 2.1 – continued from previous page

Authors	Soil type	Applied voltage or current	Electrode type	Remarks
Wu et al. (2016)	Sodium based bentonite	100V per m	Copper, Iron, Graphite, stainless steel	For all four types of electrodes, electro-osmosis decreases the plasticity index, free swelling ratio, zeta potential, and cation exchange capacity of the soil. However, much greater changes occur for the two reactive electrodes than for the two inert ones. The decrease indicates that electro-osmosis may become a potential technique for the improvement of highly expansive soils.

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Table 2.1 – continued from previous page

Authors	Soil type	Applied voltage or current	Electrode type	Remarks
Jayasekera (2015)	Alluvial soil deposit and basaltic soil deposit	0.5, 1.0, 2.0 V/cm for 7,14,30 and 60 days	Mild steel tubes	Under certain voltage gradients and processing times, around 175% and 200% strength increases are observed.
Glendinning et al. (2007)	Sewage Sludge	30V	ePVDs used as EKG	Although the best improvements in solids content derived from testing electrodes with conducting elements spaced at 5 mm and a potential of 30V the dewatering achieved appear to be more sensitive to applied voltage than to element spacing. These tests repeatedly produced solids contents of >30% after 10 min (the time representative of the residency within a belt press).

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Table 2.1 – continued from previous page

Authors	Soil type	Applied voltage or current	Electrode type	Remarks
Estabragh et al. (2014)	Soft clay soil	Electrical vertical drains (EVD) are made up of copper foil covered with a conductive polymer.	25V – 45V	The values of pH and EC of anode and cathode reservoirs are changed during the treatment time and their variations are increased with increasing the applied voltage. Increasing the liquid and plastic limits decreases the liquidity index leading to an increase in the shear strength of the soil.

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Table 2.1 – continued from previous page

Authors	Soil type	Applied voltage or current	Electrode type	Remarks
Kherad et al. (2020)	Bentonite soil	Stainless steel	0.46,0.92 and 1.84V per cm for 1,2,7 and 28 Days	The improvement of soil around the anode, where the swelling potential was reduced by up to 83%, the pH reduced up to 2.8, and the unconfined compressive strength increased by up to 800% in the best-considered test.

ions present in the solution phase of the contaminated soil move towards the cathode whereas the negative charge metal ions migrate towards the anode. These heavy metal ions concentrated at the polarized electrodes are subsequently removed either by one of the techniques electroplating, precipitation, solution pumping, or ion exchange resin complexation. Table 2.2 summarizes the various studies for the removal of different pollutants from the contaminated soil using an enhanced electrokinetic remediation technique.

Despite this, numerous extensive laboratory tests were also conducted on different soils to investigate the efficiency of stabilisation of soil with various chemicals using the EK technique. In this method, different chemicals have been used as an electrolytic solution for the stabilization of soil. The technique is also called an electrochemical method. The ingression of chemicals fills the voids of soil after getting converted into the gel and colloidal form resulting in the improvement of the geotechnical properties of soil (Winterkorn and Pamukcu, 1991). Some conventional chemicals such as sodium silicate and calcium chloride are used to stabilize the soil in the field through EK technique (Ou et al., 2009). The injection of these chemicals developed a cementitious product after undergoing a chemical reaction. Tang et al. (2021) also conducted an EK test with sodium silicate and calcium chloride for the stabilization of marine clay. The ingression of calcium and silicate ions undergoes a chemical reaction leading to the formation of CSH gel resulting in an increase in shear strength of soil by 70.4% after 14 day curing period. A similar test has been also conducted by Chien et al. (2011) to utilize sodium silicate and calcium chloride as an electrolytic solution for the improvement of the strength of silty clay. It was found that the undrained shear strength of soil was increased by an average of approximately 195% due to the formation of very stiff cemented soil after the pozzolanic reaction between chemicals. Ou et al. (2015) injected calcium chloride solution using platinum-coated titanium meshes as electrodes into the kaolinite soil after mixing with calcium hydroxide and sodium hydroxide solution. The cone penetration resistance test has been carried out to examine the effect of calcium chloride solution on strength of the soil. The injection of $CaCl_2$ solution leads to the formation of SiO_2 and NaCl products in a less alkali environment. These products get deposited in the voids of soil resulting in an increase in the strength of the soil. Whereas CSH and CAH gel are formed in the zone of higher pH zone after a longer curing period also results in an increase in strength. Chien et al. (2010) proposed a novel technique of using a relay pipe along with

Table 2.2: Removal of different pollutant form contaminated soil using EK technique.

Authors	Soil type	Applied voltage or current	Electrode type	Remarks
Méndez et al. (2012)	Hydrocarbon polluted soil	0.03 A cm^2	carbon cloth and titanium	The electrode was placed in two different arrays I) in contact with soil II) separated by a physical barrier. The removal efficiency in the array I is better than II.
Cameselle et al. (2021)	Agricultural contaminated soil with heavy metals	20V for 30 days	Titanium and stainless steel	EK technique successfully remove 78.7% of Cd, 78.6% of Co, 72.5% of Cu, 73.3% of Zn, 11.8% of Cr and 9.8% of Pb

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Table 2.2 – continued from previous page

Authors	Soil type	Applied voltage or current	Electrode type	Remarks
Turer and Genc (2005)	Artificially contaminated soil with lead, copper and zinc	250V for 30 hours	Graphite rods	The removal efficiency of lead, copper and zinc was found 48%, 92% and 32 % respectively when soil is contaminated with single heavy metals. Whereas the removal efficiencies of lead, zinc and copper were found to be 29%, 18% and 18%, respectively when soil is contaminated with all these metals together.
Wan et al. (2021)	Cadmium contaminated soil	2V per cm	Stainless steel and graphite	The removal efficiency near the anode was found to be higher at about 95.4% than at the other sampling points, where the average removal efficiency was 89.6%.

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Table 2.2 – continued from previous page

Authors	Soil type	Applied voltage or current	Electrode type	Remarks
Xiao and Zhou (2019)	Uranium contaminated soil	1V per cm for 5 days	Graphite, stainless and titanium rods	The removal efficiencies for different types of electrodes are 34.11% (graphite rod), 15.79% (stainless steel) and 18.74% (titanium rod).
Rezaee et al. (2017)	Zinc and copper contaminated soil	25V	Graphite plates	The simulation results for zinc and copper concentration profiles which were on the basis of R2 an IA calculation were in good agreement with the experimental measurements. Therefore, the proposed model with the considered assumption is plausible.

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Table 2.2 – continued from previous page

Authors	Soil type	Applied voltage or current	Electrode type	Remarks
Sivapullaiah et al. (2015)	Iron, nickel and cadmium contaminated soil	5V-60V	Graphite plate	The amount of removed Ni and Cd is generally proportional to the osmotic flow, which is about 35% and 16%, respectively. The amount of removed Fe is not proportional to the quantity of osmotic flow, which is about 1.5%.
Y. Ma et al., (2018)	Petroleum Hydrocarbon with Nickel co contaminated soil	1V per cm	Titanium and carbon plate	Under the optimum operating conditions, electro-bioremediation achieved 77.4% TPH degradation and 58.5% Ni removal after 30 days.
Kim et al. (2001)	Artificially contaminated kaolinite soil with lead and cadmium and tailing soil with lead, cadmium, zinc and copper	0.1A for 96 hours	Platinum wire	The removal efficiencies for Pb and Cd were 75–85% for the kaolinite soil and 50–70%. for the tailing soil.

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Table 2.2 – continued from previous page

Authors	Soil type	Applied voltage or current	Electrode type	Remarks
Robles et al. (2015)	Mercury contaminated soil	20V for 72 hours	vitreous carbon, Ag, and a Pt wire.	A removal percentage of 76.30% of Hg was achieved after 72 hours of treatment. a removal percentage of 84.47% of Hg^2+ was recovered when used with PRB.
Hassan et al. (2015)	Copper contaminated soil	500,750,1000, 1250 Whr	Graphite electrode	The two anode test (TAT) technique was successful in removing the copper from75% of the soil with the highest removal of 92% occurring near the anode.
Risco et al. (2016)	Soil contaminated with 2,4-dichlorophenoxyacetic acid	1V per cm	Graphite rod	The EKSF technology with parallel facing rows of electrodes can eliminateapproximately 52.89% of the pollution by electrokinetic.

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Table 2.2 – continued from previous page

Authors	Soil type	Applied voltage or current	Electrode type	Remarks
Saberi et al. (2018)	Soil contaminated with polycyclic aromatic hydrocarbon and lead (Pb), zinc (Zn), and nickel (Ni) as heavy metal pollutants	1.5V per cm	Stainless steel	The highest removal percentage of PHEwas 61%. Whereas the order of removalof heavy metals was zinc >nickel >lead,and zinc had the highest removal rate of 63%.

the anode and cathode. The installation of relay pipes in the soil is used for the injection of electrolytic solutions. The results show that the injection of the chemical through relay pipes increases the cementation area by 1.5 times and the average cone resistant value of silty clay is increased by 2 times. However, the cone penetration value is increased by 9 times and the cementation effect has been observed in the entire soil specimen when the injection of chemical is done by both the anode and the relay pipe. Keykha et al. (2014) employ the MICP solution for soft clay stabilization via the EK technique. In this method, calcium chloride solution and urea solution were injected into the anode chamber, and the live bacteria were injected into the cathode chamber. The injection of MICP solution leads to $CaCO_3$ precipitation in the voids of soil, which results in an increase in the shear strength of the soil. The shear strength of soft clay increases from 6 kPa to 52-65 kPa with a carbonate percentage of 10–18%, respectively.The improvement in the engineering properties of soft soil through $CaCO_3$ precipitation is also achieved by the use of $CaCl_2$ and Na_2CO_3 as anolyte and catholyte solutions in the EK technique (Abiodun and Nalbantoglu, 2022). The shear strength of soil increases from 21 kPa to 92 kPa with the use of calcium chloride and sodium carbonate as ionic solutions. The application of electrochemical methods needs special care. The variation in pH value near the anode and cathode affects the efficiency of the EK technique (Mosavat et al., 2012).

2.9 Summary

This chapter has outlined the major developments in the field of alkali-induced heaving studies and its suppression techniques. Although the researchers have witnessed a great advancement in this particular field, there are still some lacunae which need to be addressed further. Extensive research has been conducted on evaluating the potential of different concentrations of alkali solution on the heaving of soil but it is worth noticing that the amount of percentages heaving not only depends upon the concentration of alkali solution but also on the index properties of soil. The soil containing a large amount of clay shows a good amount of heaving at a lower concentration of alkali solution. The basic mechanism involved behind the alkali-induced heaving is that the interaction of alkali to soil leads to the accumulation of negative charges on soil particles, which causes repulsion of clay particles, and in the second stage the alteration in minerals of soil after alkali interaction which are responsible for larger swelling in samples. Various suppression techniques that are in practice have also been taken up for a detailed discussion. Many of the methods mentioned above are currently at the experimental stage, The use of different waste materials (lime, fly ash, GGBFS), some salts, etc. have been popular and extensively employed techniques. However, these techniques are not suitable for already developed sites as they cause excessive disturbance to the existing structures. With rapidly developing infrastructures, it is rarely possible to get a bare site for new constructions. In such scenarios, passive site remediation can be considered an all-safe solution. Many researchers have implemented electrokinetics into practice to stabilise almost types of soils. It is expected that the electrokinetic technique has a great potential to stabilize the soil in the field.