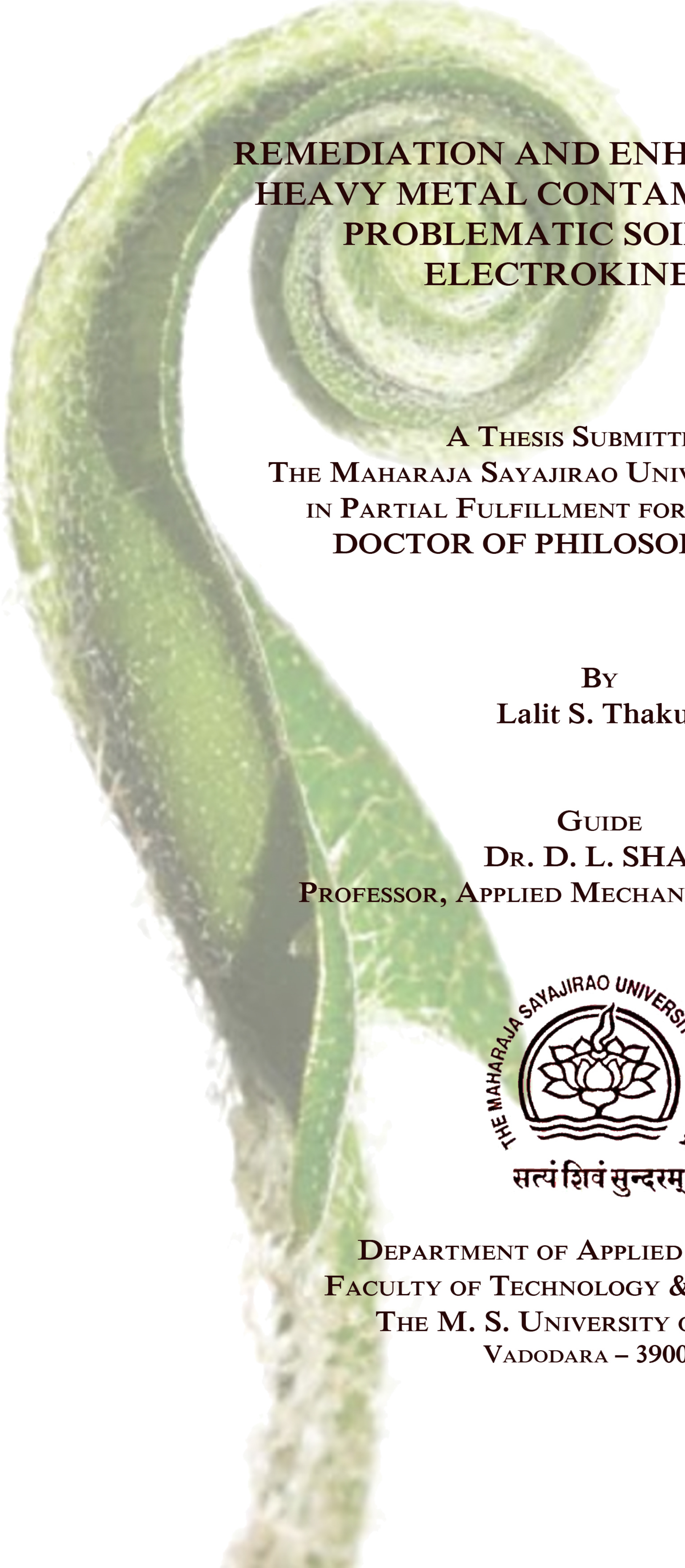

REMEDIATION AND ENHNACEMENT OF HEAVY METAL CONTAMINATED AND PROBLEMATIC SOILS USING ELECTROKINETICS

A THESIS SUBMITTED TO
THE MAHARAJA SAYAJIRAO UNIVERSITY OF BARODA
IN PARTIAL FULFILLMENT FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY (CIVIL)

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VADODARA – 390001

सत्यं शिवं सुन्दरम्

THE MAHARAJA SAYAJIRAO UNIVERSITY OF BARODA

Certificate

This is to certify that the thesis entitled REMEDIATION AND ENHANCEMENT OF HEAVY METAL CONTAMINATED AND PROBLEMATIC SOILS USING ELECTROKINETICS submitted by **Mr. Lalit Surendrakumar Thakur** represents his original work which was carried out by him at Applied Mechanics Department, Faculty of Technology and Engineering, The Maharaja Sayajirao University of Baroda, Vadodara under my guidance and supervision for the award of the Degree of Doctor of Philosophy in Civil Engineering.

The matter presented in this thesis has not been submitted anywhere else for the award of any other degree.

Vadodara
March 2013

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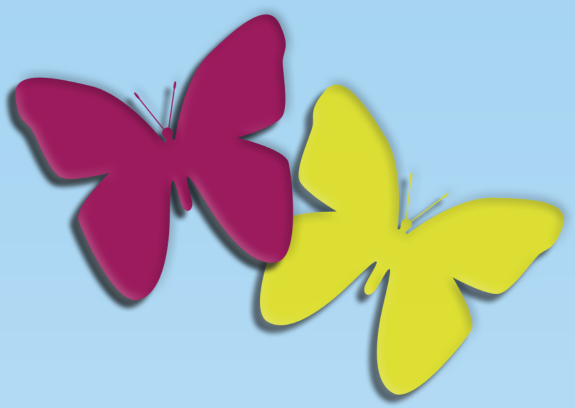
indebted

to the divine spirit
god,

to the martyrs who
taught us how
to be free &
all those who
made india proud



DEDICATION

My existence, my being and identity is dedicated to my
beloved parents, **Kanta & Surendrakumar Thakur**.
They provided me the environment and opportunities
that they never had, to pursue all my dreams.

They are the wind beneath my wings.

This research is also dedicated to my dear wife **Chanchal**
whose unflinching support and constant encouragement
enabled me to sail through this journey with ease.

This work is also for my angel & sweet daughter, **Vedika**,
whose twinkling eyes often said this to me
“ when will my papa have time to play with me?”
and for bearing my
prolonged absence due to my research.

I also dedicate this work to my brother **Kiran** and
sister-in-law **Pooja** for being there for me always
and supporting me.

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"The land of Vedas, the remarkable works contain not only religious ideas for a perfect life, but also facts which science has proved true. Electricity, radium, electronics, airship, all were known to the seers who founded the Vedas." - **Wheeler Wilcox (American poet)**

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March 2013 **Lalit S Thakur**
Vadodara

Abstract

The present thesis is a contribution to the study, from the perspective of geotechnical engineering, of the issues related to the electrokinetic phenomena in soils. Electrokinetic phenomena are here analyzed and studied together with all the broader phenomena generally connected to the induction of a continuous electrical field in saturated soil masses. In the last few years, interest in electrokinetic phenomena in soils has gained new momentum, in virtue of industries connected to soil remediation from ionic and not ionic contaminants. Indeed remediation of polluted sites through a direct current (DC) electrical field can be particularly appealing when the soil has a very small permeability, such to require long operational times with other more traditional techniques. Background knowledge necessary for a correct analysis and understanding of the electrokinetic phenomena in soils include elements from electrochemistry, water chemistry and mineralogy.

The current status of electrokinetic remediation was examined to provide background information on this matter. In addition, the evaluation of the current status was conducted to justify engaging the present research effort. L. Casagrande (1952, 1983), Mitchel J. K. (1967), and Hamnett R. (1980) were the pioneers to indentify the movement of water molecules and charged ions under influence of an electric field. Latter on Acar, Yalcin B. Alshawabkeh, A. N. (1993), Gale, R., Alshawabkeh, A. N., (1995),Virkutyte, J., (2002), Chou, S.B., and S.C.Yen, (2004), made efforts for describing the principles and status of electrokinetics. Several contributions have been dedicated to report the successful application of electroremediation on different type of porous matrices with different type of contaminant agent. Acar, Yalcin B.; Hamed, Jihad (1991), Lindgren, E. R.; Mattson, E. D., (1994), Saichek, Richard (1995), Kelsh, D. J., (1997), Puppala, S., Alshawabkeh, A. N.; Acar, Yalcin B.; and others (1997), Czurda, K. A.; Haus, R. (2002), Reddy, K.; (2002) suggests at least three general conclusive ideas about electroremediation. First, the technology is applicable to metal and organic contaminants removal. Second, it indicates that electrokinetic works well under unsaturated and saturated soil conditions. Third, low permeability soil can be treated successfully by this technology. To enhance the effect of electroosmotic improvement, injection of chemical solutions into soil during electroosmosis was adopted in recent years by Ozkan et al., (1999), Lefebvre and Burnotte, (2002), Alshawabkeh and Sheahan, (2003), Otsuki et al., (2007), Ou et al., (2009), Chien et al. (2009),Chang et al. (2010). Jones et al.(1996) and Nettleton et al. (1998) introduced the concept of electrokinetic geosynthetics (EKG), a range of geosynthetic materials that, in addition to providing filtration, drainage, and reinforcement, are enhanced to conduct electricity.

The present study is a step forward to identify and formulate a systematic approach for the practical application of electrokinetics in field employing extensive experimentation. The work also is an effort in using electrokinetics as a tool to aid grouting along with in house designed & developed conductive geotextiles for use as an aid for electrokientic dewatering not only as a replacement to use of conventional electrodes but also an efficient cost cutting tool . The knowledge database thus obtained in the analysis shall provide a deeper understanding about the behaviour of the system as a whole, leading to improvement in guidelines for increasing remediation efficiency for a particular application as the case maybe.

The first part of the study evaluates the extent of nickel removal by applying only DC current in a low permeable soil for which an electrokinetic reactor was fabricated in-house, to find a tailor made combination of purging solution using different electrode configurations at various applied voltages. Tests were performed to study the various factors affecting the process viz. size of model, concentration and type of anodic and cathodic purging solutions, voltage gradient, contaminant concentration, periodic supply, and low frequency AC supply as well as the effect of nickel concentration variation in soil. The percentage removal for all the experiments varied from 32% to 89%. It was observed that on using EDTA and NaCl as purging solutions, maximum percentage removal of nickel from the contaminated soil was observed. Increasing the voltage and the cross sectional of the area and reducing the electrode spacing increases the removal efficiency to about 85%, but reduces when calcium chloride is used instead of sodium chloride the removal drops down to 21% for a particular case. The behaviour of the metal removal was analyzed only in the individual state.

The sole target of the next section of the study was to analyze the method of electrokinetic chemical grouting as a tool to inject chemical grouts into soft soils at sites where the conventional methods cease to work efficiently. The parameters for the study included varying the concentration of grout, the type of fine grained soil to be improved, duration of the process, concentration and type of reactant i.e. hardener, applied voltage gradient, electrode spacing, periodic supply, low frequency AC supply and size of electrokientic reactor. The efficiency of the method was evaluated with the use of strength and permeability measurements pre and post process as well as during the process validated by use of scanning electron microscopy (SEM) & energy dispersive spectroscopy (EDS) to analyze the soil samples collected from different compartments of the electrokientic reactor. It was observed from the results of electrokinetic grouting experiments that flow of grout was more efficient in sandy silts and sands as opposed to clayey soils, though it is noted that the flow can be increased by increasing the voltage gradient applied. A maximum decrease in permeability of about 238% was observed in silty soil collected from the campus whereas the maximum decrease of 85% in permeability was observed in sandy soil collected from Hajira. The results obtained from the unconfined compressive strength test showed an increase of strength by 2.5 times compared to the original strength where 20% sodium silicate solution was used. In case of 25% and 30% concentration, the increase in strength was observed to be 3 times and 3.3 times more than the original strength respectively after electrokinetic grouting experiment.

The third section of the study was to identify the potential benefits of eKG for dewatering of soft soil slurries or sludges. The eKG's were designed and woven in house using a variety of commercially available raw materials and using nano conductive particles for coating on nonwoven geotextiles. Appreciable percentage removal of water was observed with the use of all the conductive textiles prepared, compared to that observed due to gravity or percentage water loss caused by air drying. A significant soil volume and water mass reduction was observed after EK treatment. Six different soils and one vermi-compost was studied to understand effect of soil type on dewatering. The reduction of water content in different soils ranged from 8%(flyash) to 40%(CH) within 3 days of electrokinetic dewatering. A corresponding increase was observed in vane shear strength varying from 60% to 140%.The maximum water removal (39%) was observed in cotton yarn & steel filament x cotton yarn & steel filament (warp x weft) whereas the minimum water removal (28%) was observed in copper wrapped polyester yarn x copper wrapped polyester yarn (warp x weft). The selection of electrode material proved to be a crucial aspect for successful application of EK dewatering. Efficiency of conductive coating on nonwoven Geotextile as a cathode for dewatering studies proved polyaniline based conductive coated nonwoven geotextile gives the maximum water removal of 24%. Electrokinetic prefabricated vertical drains were used for dewatering of deep soft soil layers showing a reduction of 38% from initial water content in 48 hours, presenting it as a viable alternative for the in-situ dewatering of soft soils, lagoons containing sewage sludge (or other difficult materials). The development of EKG in general and ePVDs in particular may prove to be a break through pathway to provide effective in-situ treatment of problem materials such as deep layered soft soils and sludge lagoons by avoiding the costly and environmentally intrusive alternatives.

A regression model was developed for both electrokinetic remediation of nickel contaminated soil as well as electrokinetic grouting. The model turned out satisfactory with above 70% reliability for electrokinetic grouting in prediction the % UCS increase and another model for predicting % permeability decrease. For electrokinetic remediation it did not provide a suitable solution, in which case an ANN based model was developed with one, two and three hidden layers providing upto 98% reliability with the results obtained compared to those observed experimentally.

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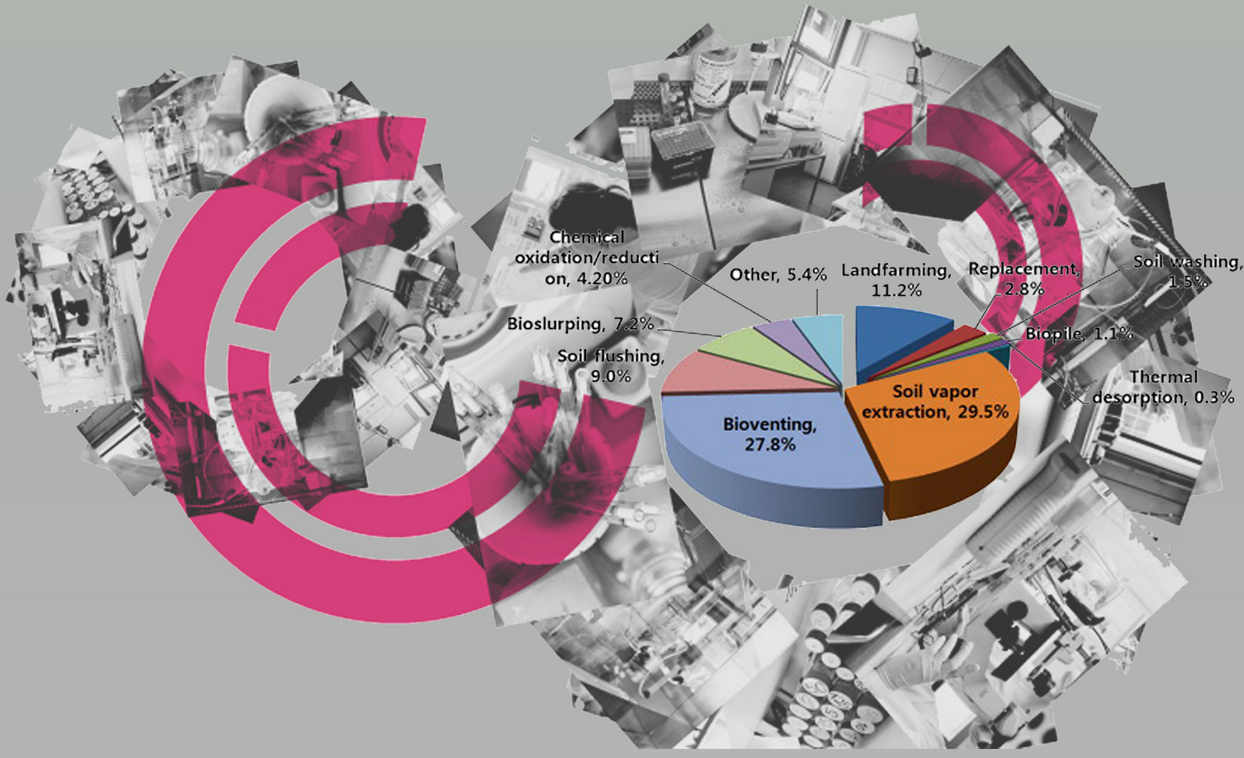
CHAPTER 1

Introduction



Introduction

Chapter One

Land, a broader concept of soil, has been defined by the International Food and Agriculture Organization (FAO, 1976) as: *"An area of the earth's surface, the characteristics of which embrace all reasonably stable, or predictably cyclic, attributes of the biosphere vertically above and below this area, including those of the atmosphere, the soil and the underlying geology, the hydrogeology, the plant and animal populations and the results of past and present human activity, to the extent that these attributes exert a significant influence on present and future uses of the land by man."*

This definition requires full interaction between the four ecosystems, i.e., *atmosphere, hydrosphere, biosphere and geosphere,* which constitute the land. The atmosphere is the envelope of gases surrounding the earth. Hydrosphere refers to water in various forms. Biosphere refers to living organisms and their environments on the surface of the earth. Finally, the term geosphere refers to the complex and variable mixture of minerals, organic matter, pore fluid, and air that make up the soil.

Soil is the thin layer of organic and inorganic material that covers the Earth's rocky surface. The organic component, which is derived from the decayed remains of plants and animals, is concentrated in the dark uppermost topsoil. The inorganic component made up of rock fragments, was formed over thousands of years by physical and chemical weathering of bedrock. To the civil engineer, soils are any uncemented or weakly cemented accumulation of mineral particles formed by the weathering of rocks, the void space between the particles containing water and/or air. Weak cementation may be due to carbonates or oxides precipitated between the particles or due to organic matter.

1.1 PROBLEMATIC SOILS AND CONTAMINATION

It is rare to have a naturally occurring perfect soil that is ideal for construction or its intended use. Many areas of the world consist of soils with high silt contents, low strengths, and minimal bearing capacity. The strength and stability of such soils can present problems during construction and certainly can affect the long-term performance of the structure during its service life. Many soils can prove problematic in geotechnical engineering because they expands, collapse, undergo excessive settlement, have a distinct lack of strength or are corrosive. Geotechnical design and execution of civil engineering structures on/in soft to very soft soils are usually associated with substantial difficulties. Since these type of soils are sensitive to deformations and possesses very small shear strength, they may lead to structural damages during the execution as well as throughout the life of the projects especially in urban areas.

This can be due to:

- excessive settlements or tilting of newly constructed building structures,
- entrainment settlement of old structures near newly erected structures,
- an adverse effect of excavations on nearby structures, etc.

The expanding scope of human activity, pursuant to the industrial revolution, has steadily overweighed the global environment. The situation has been made all the more serious by the expansion of the global economy and the increase in population since World War II. Every area of our planet's life support system, i.e., air, land, water, and natural ecosystems, is showing signs of damage, as evidenced by:

- pollution of air, land, and water,
- water scarcity and degradation,
- global population increase,
- growing quantities of wastes,
- trans-boundary movement of hazardous waste,
- acid rain,
- deforestation in terms of land degradation and its contribution to climatic change,
- desertification and soil erosion,
- global warming,
- depletion of the ozone layer, and
- decreasing species of wildlife.

Soil pollution is defined as the build-up in soils of persistent toxic compounds, chemicals, salts, radioactive materials, or disease causing agents, which have adverse effects on plant growth and animal health. The movement within the land has a profound effect upon its bioavailability. The rates of transfer of these pollutants are important and can affect the land livability. Once a pollutant enters one of the mobile phases, i.e., air or water, it disperses rapidly within the soil due to fluid movements. Movement within a phase i.e. mass transfer, diffusion, or dispersion, is important to the movement of pollutants between the various phases of the ecosystem. Humans and other organisms that constitute the biosphere, reside to varying degrees, within the other three spheres. Several direct and indirect routes of contaminants through the land and eventually to humans exist and are shown in Figure 1.1.

Contaminated land is defined as:“Any land which appears to the local authority in whose area it is situated to be in such a condition, by reason of substance in, or under the land that causes significant harm or there is a significant possibility of such harm being caused or pollution of controlled water is being, or is likely to be caused (Section78A (2), Part II(A) of the Environmental Protection Act 1990).

The presence of contaminant sites on the earth’s surface is quite common and requires an urgent cleaning, with a lot of industrial and agrochemical processes contributing to this situation. The most dominant source of contamination is mining, petroleum spills from leaking tanks, disposal of many chemical associated with agrochemicals in farm fields, as well as discharge of many industrial processing fluids for paper making, pharmaceutical industries and radioactive material etc.

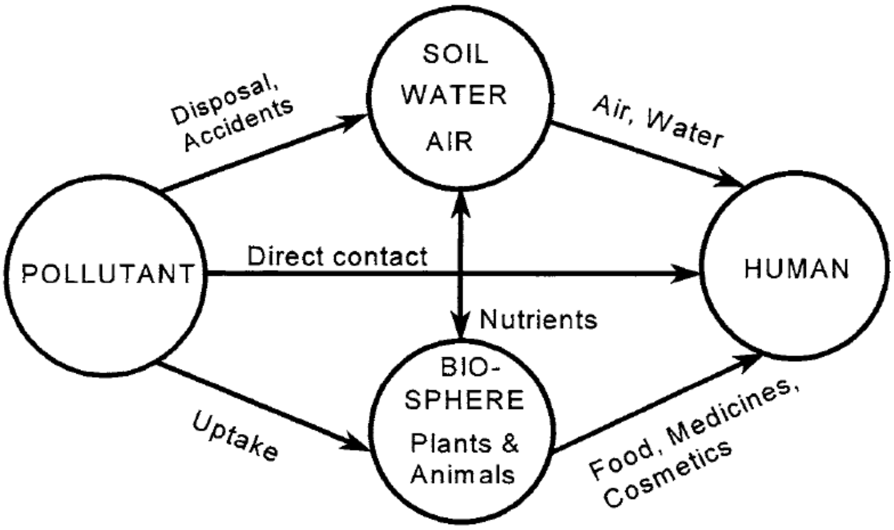


Fig. 1.1 Direct and indirect routes of contaminates

1.2 TREATMENT TECHNOLOGIES FOR SOIL REMEDIATION & ENHANCEMENT

Geotechnical engineer's task should be recognizing correctly the role of the type of soil in pollution propagation and then helping in choosing the proper technique when remediation is necessary. Remediation process is aimed at the removal of the dangerous effects of the pollutant, which can be achieved in different ways. The choice of a remediation technique has to keep into account basically the physical – chemical characteristics of the pollutants; the physical – chemical characteristics of the soil matrix and whether site conditions are of saturated and/or of unsaturated soil. As a consequence, many technological efforts have been made to "remediate" contaminated sites considering the most relevant biological and physicochemical aspects of the contaminant species, viz. dig and haul, soil washing, solidification/stabilization, vitrification, phytoremediation, electrokinetic remediation and others.

- **Dig and Haul Method:** The "dig" and "haul" method of soil remediation is an ex-situ method where the contaminated soil is excavated and hauled to an approved hazardous waste disposal location for disposal. This method was most widely used being a cost-effective remediation alternative but non removal of contaminants, the present shortage of land with its long term consequences are its biggest disadvantages.

- **Soil Washing:** It is an ex-situ treatment technology used to treat metal contaminated soils, relying on physical extraction and separation processes by concentrating them into a liquid phase form removal, generating a clean soil containing little metal contamination. Sites with mixed contaminants are hard to treat since it is difficult to formulate a suitable washing liquid that can remove all targeted contaminants. In addition, soils with mixed contaminants can be expensive to treat (U.S. EPA, 1997a).

- **Solidification/Stabilization:** Solidification/ stabilization of contaminated soils also involve either in-situ or ex-situ processing, wherein specialized additives or reagents eg. flyash, cement and/or kiln dust are mixed with contaminated soil to reduce solubility and/or mobility of the contaminants. Although proven to be effective in immobilizing heavy metal contaminants, contaminant remobilization is possible due to the deteriorization of the binding agents or a change in pH. Solidification/stabilization does not remove the contaminants from the soil matrix but is targeted to contain them. (Orcino, 1995).

- **Vitrification:** Vitrification is a thermal treatment process that can be used to treat contaminated soils both in-situ and ex-situ. It is a process that converts contaminated soils into a stable glassy form using an electric current between an array of graphite electrodes, which heats the soil to very high temperatures (1,500-2,000°C), melting the soil to form stable glass thereby immobilizes the metals. An off-gas hood is placed over the treatment area, to collect and treat any off gases (volatile metals) released during the treatment process (U.S. EPA, 1997a).

- **Phytoremediation:** Phytoremediation is an in-situ treatment technique that utilizes natural properties of plants to remediate contaminated soils, involving two basic approaches for treatment i.e. phytoextraction and phytostabilization. Phytoextraction involves uptake of metal contaminants by the plants from the contaminated soil, from where they are then transported into the roots and above ground plant tissue. The contaminated plants are harvested and treated or disposed, with its cost dependant on the amount of biomass produced, concentration of contaminants, and number of times the crop has to be harvested. With phytostabilization, the contaminants are immobilized through secretions of chemicals produced by the plants at the interface of the roots and soil also helping to stabilize soil by reducing effects of erosion. These chemicals react with the metals producing immobile complexes. This treatment technology is best suited for sites with widely dispersed contaminants at low concentrations, but should be limited to root zone of plants (U.S. EPA, 1997a).

- **Electrokinetic Remediation:** Electrokinetic remediation involves the application of low-density direct current between electrodes placed in the soil in order to mobilize contaminants in the form of charged species. Electrokinetics can be used to extract radionuclides, metals, and organics from saturated and unsaturated soils (U.S. EPA, 1997). As an in-situ treatment method, it offers the removal of organic and inorganic contaminants at a relatively low cost compared with other technologies. The applicability of this method in clayey soil is considered a breakthrough in the process of soil decontamination.

1.3 BACKGROUND OF ELECTROKINETICS

Electrokinetics has evolved from the studies of electricity. In the 18th century Louigi Galvani, studied transport across cell membrane possessing a potential difference. He discovered that muscle in the legs of frog twitched in the presence of a source of electrical charge or when the muscle was touched by a metal. Allessandro Volta was the first to interpret correctly Galvani's result by pointing out that the twitch was a result of a change in external potential differences. It was early in that century that Michael Faraday was able to show the relationship between the amount of electricity produced and the amount of chemicals that react at an electrode. By the later part of the 19th century, it was well known that solutions could conduct electricity. It was at this time that Svante August Arrhenius proposed the concept of ions as electrically charged atoms or molecules, and that it was these species that were responsible for a solutions ability to support an electric current. Although in many instances successfully applied, the effectiveness and efficiency of electrokinetics for heavy metal removal has been questioned by field engineers. Contradictory to this belief, applying electrical fields to soil has emerged as a path breaking technology which is receiving prime attention today.

1.3.1 The Process

Electrokinetic remediation is a relatively simple process which involves the use of two electrodes, which are placed within the contaminated soil volume while a direct electric current (DC) is passed between them creating an electrical field. As a result, one of the electrodes becomes the anode, the other becomes the cathode completely developing the transport mechanisms in the zone that separates these two electrodes (Fig. 1.2). This zone, also called Treating Zone, where migration of ions is observed in the direction of the electrodes. Positive charged ions move towards the cathode and negative charge towards the anode.

The increased concentration of the ions and/or particles in the neighbourhood of the electrode wells i.e. the electrode with the solution, sets the opportunity of extracting them from the site by pumping them out. Another important part of the process is the redox reaction taking place at the electrodes in the aqueous phase. At the positively charged anode, an oxidation reaction occurs, generating oxygen gas and giving electrons to the anode to complete the circuit:

$$2H_2O \rightarrow O_2 + 4H^+ - 4e^- \quad \text{-----------------------------}1.1$$

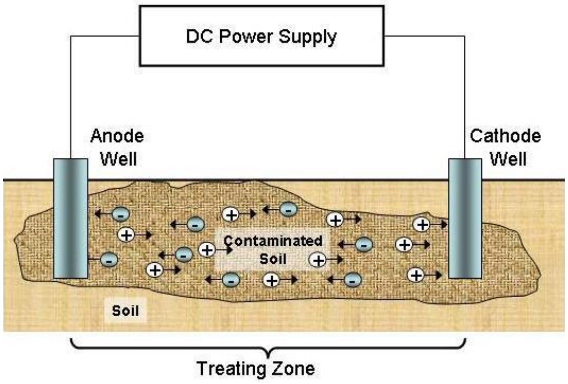


Fig. 1.2 General sketch of the electroremediation process

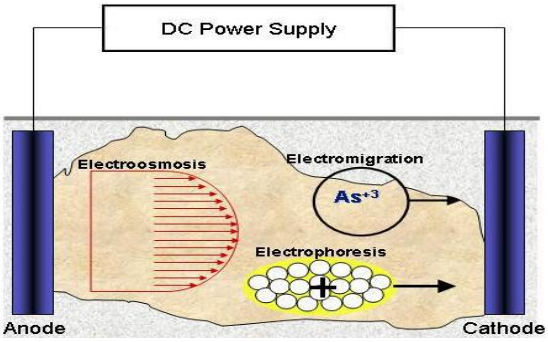


Fig. 1.3 Sketch of the electro-mechanisms in an electrostatic cell.

The result of this half-reaction is an acid front migrating to the cathode that, depending on the soil characteristics, is retarded by the soil buffer capacity. Conversely, a reduction process takes place at the cathode generating hydroxyl anions (OH-) by the following chemical equation:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad \text{--------------------------1.2}$$

This base front migrates to the anode. One would assume that both these fronts, the acid and the base would neutralize each other but the smaller hydrogen cations move faster than the hydroxyl anions. The net result is that the electrokinetic process near the cathode is acidic in nature. The conceptual description of the electroremediation process can be further enlightened; however, it is important, at this point, to understand the process basis. Variations to the intended description of this process mainly come from technological improvement. Proposed enhancements of this technology are:

- the induction of advection by using injection wells and subsequent fluid extraction via pumps,
- the use of different types of electrodes either to favour or to avoid early electro-deposition or precipitation,
- electrodes casing modifications to make it inert to ions and/or particles, and
- addition of surfactants to enhance ions mobility.

1.3.2 Governing Phenomena

To fully understand the driving forces on this phenomenon, a definition of the main concept has to be provided first. Electrokinetic remediation can be defined as the process of an applying electrical field to a soil matrix. This is done with purpose of mobilizing contaminants affected by electrokinetic forces from one electrode to the other where they concentrate. This specific electrode is the point of removal of contaminants via some type of mechanism. Based on what was mentioned before, in regard to moving contaminants, under the presence of an applied electrical field, the three basic mobilizing mechanisms are: Electroosmosis, Electromigration, and Electrophoresis. Fig. 1.3 illustrates these electro- mechanisms and the most typical definition for each these terms are as follow:

1.3.2.1 Electroosmosis

If an electric potential is applied across a wet soil mass, cations are attracted to the cathode and anions to the anode. There is an excess of cations in the system to neutralize the net negative charge on the soil particles. As these cations migrate to the cathode, they drag water with them, causing water movement towards the cathode, as shown in Fig. 1.4a. The anions also drag water with them as they migrate to the anode. This flow is usually less than the flow to the cathode; consequently there will be a net flow of water to the cathode end which is referred to as electroosmotic flow.

1.3.2.2 Streaming Potential

When water is caused to flow through a soil under a hydraulic head difference, Fig. 1.4b, double layer charges are displaced in the direction of flow. The result is an electrical potential difference proportional to the hydraulic flow rate, termed the streaming potential, between the opposite ends of soil mass. Streaming potentials of several tens of mV have been measured in clays using a high internal impedance voltmeter (Mitchell, 1993).

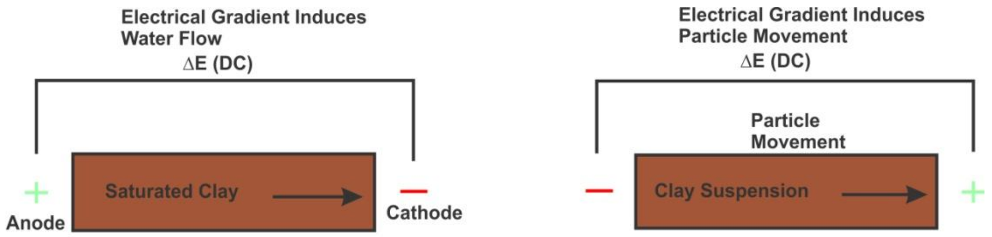
1.3.2.3 Electrophoresis

If a direct current is applied across a colloidal suspension, charged particles are attracted electrostatically to one of the electrodes and repelled from the other. Negatively charged clay particles move towards the anode as shown in Fig. 1.4c. This is called electrophoresis, which involves discrete particle transport through water, whereas electroosmosis involves water transport through a continuous soil particle network (Mitchell, 1993).

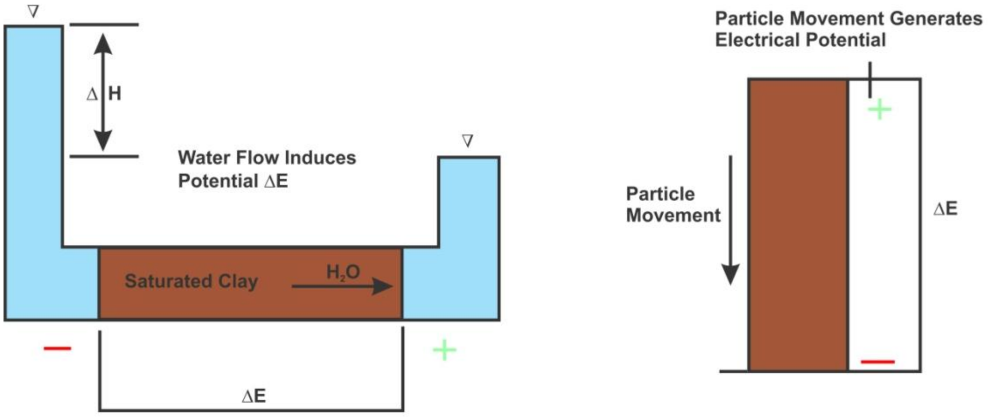
1.3.2.4 Migration or Sedimentation Potential

The movement of charged particles, such as clay, relative to a solution during gravity settling, leads to generation of a potential as indicated in Fig. 1.4d. This is caused by the viscous drag of the water that retards the movement of the diffuse layer cations relative to that of the particles. Among the four electrokinetic phenomena, electroosmosis has been given the most attention in geotechnical engineering for the last five decades, due to its practical value for transport of water in fine-grained soils with low permeability. These electro-mechanisms, although the most significant, are not the only mechanisms governing the electrokinetic remediation process. There are some mechanisms that participate in this process; i.e. advection, convection, and diffusion/dispersion. These mechanisms can be defined as follows:

- Advection is the movement of soil moisture or groundwater as a consequence of hydraulic forces (Darcy’s Law).
- Convection is the movement of soil moisture or groundwater as a consequence of buoyancy forces.
- Diffusion/dispersion is the transport of molecular particles due to a concentration gradient as a driving force or due to mechanical conditions of the soil.



(a) Electro-osmosis (c) Electrophoresis



(b) Streaming Potential (d) Migration Potential

Fig. 1.4 Electrokinetic Phenomena in Clay (Mitchel, 1993)

These mechanisms may be present although electrostatic forces may not affect the system. However, when an electrostatic field does influence the system, the mechanisms of advection, convection and diffusion/dispersion are augmented and work along with the electro-mechanisms. Furthermore, when this takes place, it is very difficult to distinguish very clearly between one and the other mechanism, so most scientists summarized them as just electroosmosis, buoyancy, and dispersion, this is, electroosmosis as a consequence of applying electrical field, buoyancy as a result of the advection produced by the joule heating effect, and dispersion as a result of the gradient in concentration being generated. Neglecting to fully name the involved mechanisms does not necessarily mean that they are not part of the process.

1.3.3 Electrokinetic Technologies

When theory is applied it can develop into many different forms of technology. The functional principles of using two electrodes can be converted into a complex arrangement of a single cathode and many anodes. This type of design was and is one of the many intents to produce some results in site clean ups but of course, more structured designs are used which can be divided into two main groups. The first group is composed by those technologies that have passed field tests fairly well; these are: a) Cation Selective Membrane, b) Ceramic Casting, c) Lasagna, and d) Electrochemical ion exchange. The second group corresponds to those technologies that still need some more laboratory and field testing; these are: a) Electrokinetic Bioremediation, b) Electrochemical Geo-oxidation, and c) Electrosorb.

- **Cation Selective Membrane:** This type of application is able to target specific cations of contaminant for removal. Using a membrane as an ions barrier, only the cations that are small enough to go through the porous membrane will reach the cathode. Selectively, those are cations that are targets for removal (Fig. 1.5).

- **Ceramic Casting:** There has been a misconception about the ability of electrokinetics to produce good results on unsaturated soil. Some case studies indicate that this variable can be controlled as pH to improve removal, this being the underlying principle of using ceramic casting, where in a controlled volume of contaminated soil, buffer solution is added to ensure a constant value of water content as well as pH. (Fig. 1.6)

- **Lasagna:** Lasagna technique can be applied in a horizontal and in a vertical array, the overall process taking advantages of the electroosmotic flow (Fig. 1.7). In other words, the bulk movement of water (contaminants included) is due to an electrostatic field. This movement grants the incursion of water from anode to cathode through the degradation zone. Within the degradation zone different layers of sorbents, catalytic reagents, buffering solutions, oxidizing agents, and others are placed. It is from this practice that Lasagna obtained its name. The net result is that contaminants are degraded as they encounter the battery of chemicals previously added and only those constituents very hard to remove reach the cathode.

- **Electrochemical ion exchange:** The method uses an electrode to charge the electrolyte, with the electrostatic field still in place. (Fig. 1.8). As the ions migrate and dissolve in their respective electrolytes, the electrolyte of each end is passed through an ion exchange device to capture the target ions. The device frees the electrolyte from ions and regenerates its ability to pick up more contaminant ions from the soil. This cycle is repeated over and over again until the target efficiency is reached.

1.3.4 Advantages and Disadvantages of Electrokinetics

The pros and cons of the electrokinetic technology are mainly discussed in terms of operation and efficiency. Common advantages reported by different authors are as given below:

- In Situ method for removal.
- Restricted treatment area.
- No excavation is required.
- It can be designed for specific targets.
- Targets are heavy metals, anions, and polar organics in soil, mud, sludge, and marine dredging.
- Chemicals can be used for enhancement.
- Less energy demand.
- Site abandon is easy and clean.

- Applicable to low permeability soils.
- Applicable to saturated and unsaturated soil.

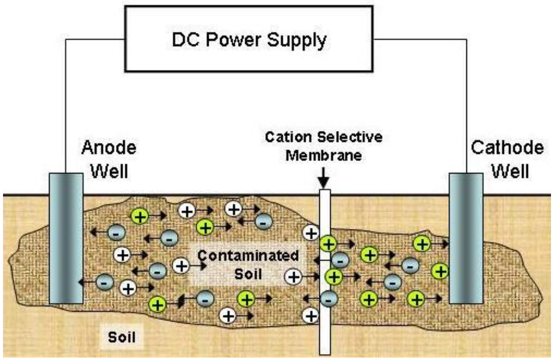


Fig. 1.5 Cation selective membrane process sketch

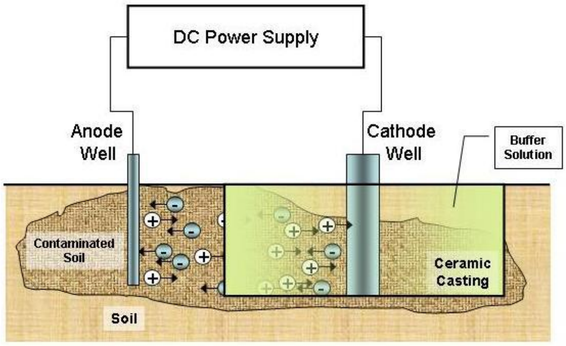
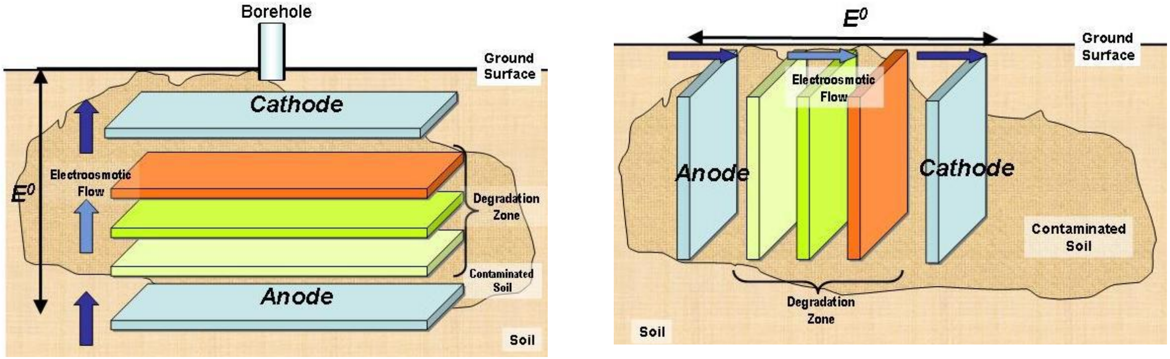


Fig. 1.6 Ceramic casting process sketch



(a) (b)

Fig. 1.7 Lasagna process sketch for the (a) horizontal, and (b) vertical arrays.

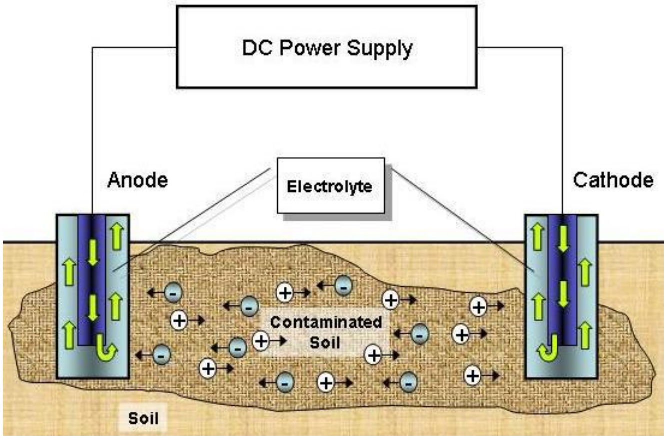


Fig. 1.8 Electrochemical ions exchange process sketch.

Although promising, electroremediation also offers some evident issues. Some of the most recurrent disadvantages are as listed below:

- Electrical field distortion may occur and contaminants will follow on an unpredicted path.
- Other ions may interfere with the target ions removal.
- Fragile equipment is required.

- Efficiency reduced for moisture content < 10%.
- Corrosion may be a big cause of concern in some cases.
- Temperature effect may reduce effectiveness.
- Redox reaction may yield undesirable products.
- pH control may be highly required.

Despite the number of applications that can be listed, the applied electrical field technologies have remained non-spread for several reasons. The unavailability of electrode materials that are resistant to corrosion and the poor understanding of the electrokinetic transport associated with the fundamental processes have contributed in part to this status. Studies performed by various researchers in the field clearly state that, there is lack of understanding of the shape and placement of electrodes, type and extent of remediation required, form of presence of contaminant, type of soil and spread to be treated along with the depth of soil layer and climate specific factors. These elements are a key for proper design of the system, which when overlooked and/or unintentionally skipped can considerably affect the movement of ions and affect the overall removal efficiency of contaminants. Furthermore, for cases wherein the spread is small, but the contaminant has drastically affected the geotechnical properties of the soil, remediation alone does not suffice but requires the soil to be improved along with the removal. In such cases, a specific ground improvement technique needs to be used wherein both the purposes can be solved simultaneously or at least taken care of in some percentage. All these unknowns, mentioned above, suggest that there is a lack of systematic analysis of the different aspects governing the process.

In fact, there are no prior design criteria for different electrokinetic applications that could help to design a device in the form of a mathematical or a neural network or a protocol for the cleaning of a contaminated site.

1.4 RESEARCH OBJECTIVES

The overall goal of the present study is to evaluate and enhance an electrokinetic remediation system to be suitable for the efficient removal of nickel from clayey soil and for improvement of problematic soils with either grouting or removal of excess moisture. To accomplish this objective, following goals were established:

- The primary objective of this research was to evaluate the extent of nickel remediation by applying only DC current in a low permeable soil. To achieve this goal an electro-kinetic reactor was fabricated and a test plan was prepared. Low voltage DC voltage was applied in soil to see the extent of remediation.
- This study also intended to find a tailored made combination of purging chemicals for additional enhancement of nickel remediation. Different enhancement solutions; such as acids, alkali and oxidizing agents were tested, and purged through the system by using the natural phenomena of electrokinetics. Configuration of electrodes/reactor setup was also adjusted to increase the removal efficiency of nickel.

- In addition, the study was extended to analyze the mechanisms of nickel removal. The variables for this part of the study included different sizes of reactor’s set-up, and optimal purging solutions. The sequence of experiments was exclusively designed to study possible differences in removal efficiency with different electrode spacing, cross sectional area and the possible use of low frequency AC supply. Concentrations of nickel in the soil mixture were chosen based on the common concentrations found at the different nickel contaminated soil samples.
- The secondary objective of the study was to analyse the method as a tool to inject chemical grouts into soft soils where the conventional method ceases to work efficiently. The variables for the study included the different concentration of grouts along with the type of fine grained soils. The efficiency of the method was evaluated with the use of strength and permeability measurements pre and post process as well as during the process duration.
- An attempt to design a conductive geotextile using a variety of commercially available raw materials for application in electrokinetic dewatering.
- Development of an artificial neural network along with its validation using experimental results for nickel contamination removal as well as electrokinetic grouting technique.

1.5 IMPORTANCE OF THE STUDY

Two main motives are intended to justify this research effort: the potential use of electrokinetics for contaminant removal and remediation and the anticipated scientific contribution of a modelling of the electrokinetic phenomenon.

1.6 ORGANIZATION OF THE THESIS

The work carried out in this thesis deals with the application of electrokinetics for remediation of heavy metal contaminated soil as well as improvement of soft soils using electrokinetic grouting or dewatering. It comprises of eight chapters outlined as below:

Chapter 1, Introduction includes an introduction to problematic soils and contamination; various treatment technologies available, background of electrokinetics including the process and governing phenomena as well as different electrokientic technologies and the objectives of this research.

Chapter 2, Literature Review describes the history of electrokinetics, the details of phenomena involved in electrokinetics; contamination migration, reaction involved in electrokinetics and literature review about laboratory scale electrokinetic remediation and mobility of ions under the influence of electric field and the field applications of electrokinetics in past and present situations. This chapter also includes the history of electro-osmosis in detail, the mechanism of the electro-osmotic chemical treatment, including the electrical double layer theory, the electrokinetic principle and the chemical reaction of electro-osmosis.

Chapter 3, Electrokinetic Remediation of Nickel Contaminated Soil includes the instrumental techniques used for electrokientic remediation of Nickel contaminated soils, in house developed DC supply unit, along with the description of the method of artificial spiking of soil for the study. This chapter includes description for the construction of the electrokientic reactor, experimental procedure followed for removal of heavy metal from soil, current, temperature and pH measurements, followed by a detailed schedule outlining the experimental work for remediation of Nickel contaminated soils. Exhaustive analysis of the obtained data and evaluated parameters such as reactor size, voltage gradient, effect of anodic and cathodic purging solution, electrode spacing, low frequency AC supply and periodic supply with removal values are presented as individual experiments and group analysis.

Chapter 4, Electrokinetic Grouting for Problematic Soils includes the description of the development of an open electrokinetic reactor for the electrokientic grouting study. The chapter briefs out the experimental schedule followed for the work as well as the procedure used along with preliminary study of grout design**.** An comprehensive analysis of the obtained data, including voltage, current and current density profiles, temperature profiles, percentage improvement in permeability and post treatment strength is presented.

Chapter 5, Electrokinetic Dewatering using Conductive Geotextiles comprises of the design and development of an innovative conductive geotextile prepared in house for the use as an alternate to commercial electrodes in electrokinetic dewatering application. The instruments used are also briefly cited in the chapter alongside the experimental line up followed. The chapter concludes with an in depth analysis of the obtained data, including soil humidity, strength and water content profiles, and percentage water removal compared for various conductive geotextiles.

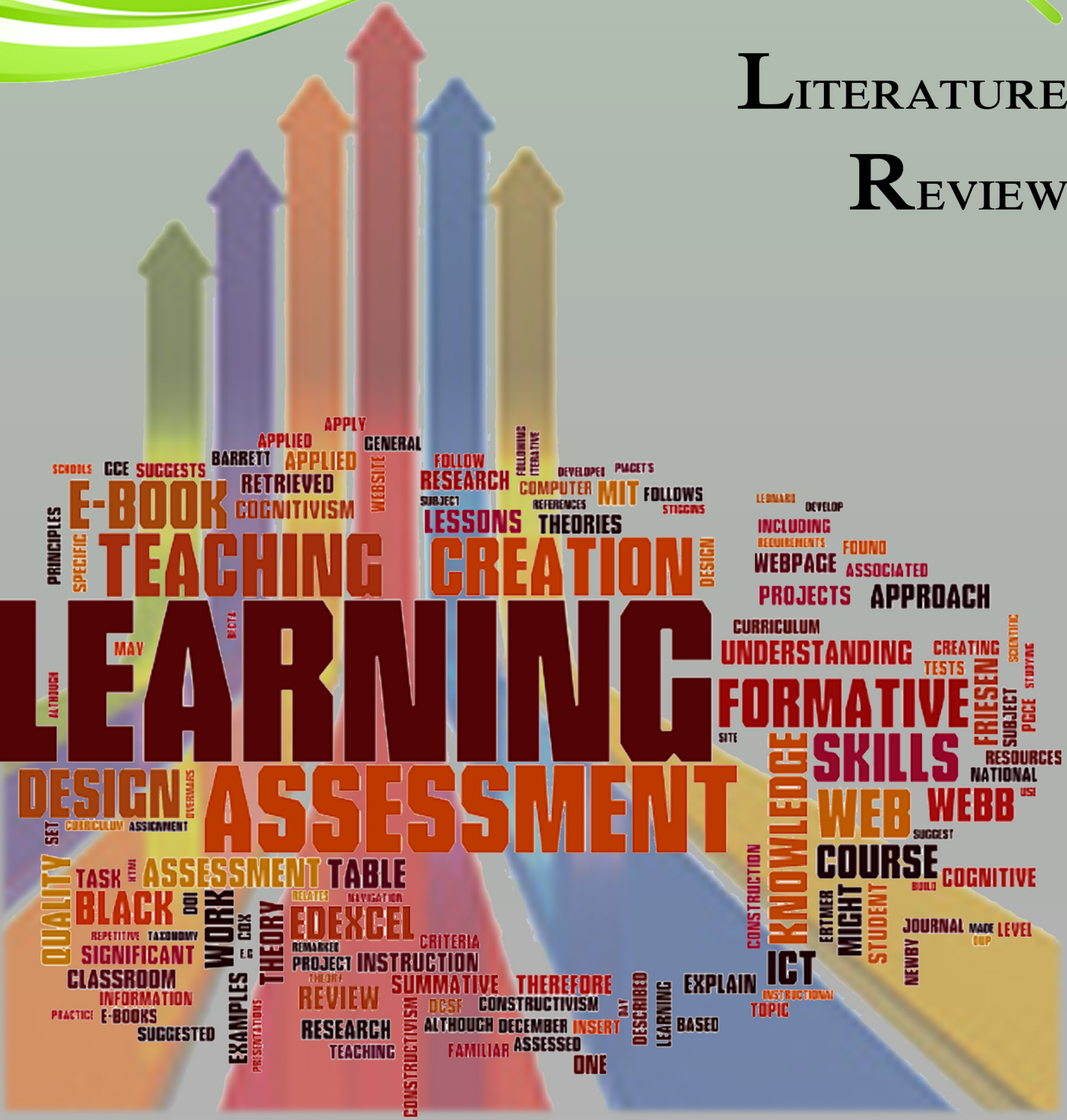
Chapter 6, Regression Modelling for Electrokinetic Remediation and Electrokinetic Grouting includes regression modeling for the remediation of Nickel Contaminated Soil and electrokinetic grouting along with importance factor study for each of the parameter considered in the study.

Chapter 7, Artificial Neural Network for Electrokinetic Remediation the various artificial neural networks used along with their parametric reliability study to decide on the most successful neural network for electrokinetic grouting.

Chapter 8, Summary of Findings is the overall conclusion, expressed on the basis of experimental findings and test results. The perspective of future works and recommendations for it are given, both with respect to geotechnical aspects as well as aspects strictly connected to soil remediation.

CHAPTER 2

Literature Review



Literature Review

Chapter Two

Heavy metal contamination of soil and groundwater is a global problem. Methods for cleaning up contaminated sites involve either long-term containment system or treatment systems (Fig. 2.1). For more than 50 years, engineers have been using electrokinetic techniques to stabilize soft soils. This electrically driven electroosmotic flow is much faster than the hydraulic flow in fine grained soils driven flow, and is also independent of the size of the flow channel and has a high degree of flow direction control. Electrokinetics can be used in both containment and treatment systems (Mitchell & Yeung 1990). For a treatment system, many field trials have shown considerable promise but have not been completely successful due to inadequate characterization (Lagernan 1993; Banerjee et al. 1990). Although it is impossible for electrokinetic remediation to solve all contamination problems, with more understanding of this phenomenon and the soil-contaminant interaction, may become a valuable tool for engineers in dealing with some of the today's complex contaminated sites.

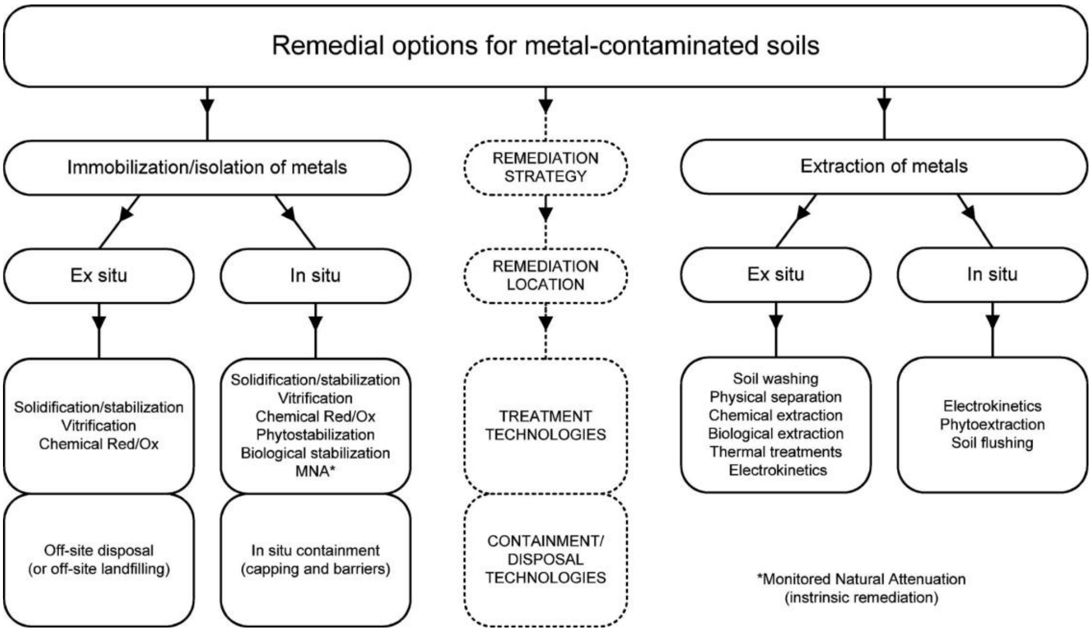


Fig. 2.1 Methods for remediation of metal contaminated soils

2.1 ELECTROKINETICS

As early as 1808, Reuss observed the phenomenon of electroosmosis. He discovered that, under the influence of an applied electrical potential, water moves through the soil capillaries from the positive side to the negative side of the cell. The theory presented by Smoluchowski (1921) is widely known as the Helmholtz-Smoluchowski theory. This theory deals with the electroosmotic velocity of a fluid in soil media under the application of an electrical gradient. In the 1930's, electroosmosis was applied to fine grain materials for soil stabilization in earthworks and foundation engineering (Gent, 1998). Casagrande

(1952) presented the basic principles of electroosmotic flow though capillary tubes. Later, he described the basic principles of electroosmosis in fine grain materials, and presented the practical applications of soil stabilization for earthen works and foundation engineering. Gray and Mitchell (1967) showed that electroosmotic flow increases as the concentration of electrolyte in the pore fluid increases. Later, Casagrande (1983) presented a summary of electroosmotic theory, electrical conductivity, electroosmotic permeability, water content, stability limits, as well as providing a methodology for calculating electrode spacing. Electrokinetics has undergone a great deal of change as it evolved to its current state. The following sections provide a brief window into electrokinetic's recent laboratory scale investigations.

Isomorphous substitution and broken continuity of structure present a net negative charge at the surface of clay particles. To balance the negative charge, the clay particles attract positively charged ions from salts in their pore water. The attraction of cations and repulsion of anions in clay particles, leads to a distribution similar to Fig. 2.2. This figure shows a decrease in cation concentration and increase in anion concentration with distance from the clay surface. When the clay is placed in water, the dipolar water molecules can be electrically attracted toward the surface of clay. The negative surface charge of clay and the electrically attracted water are together termed the diffuse double layer. The nature and thickness of the double layers, will affect the clay characteristics. In general, the tendency for particles in suspension to flocculate decreases with increase of thickness of the double layer. Coupling between electrical and hydraulic flows and gradients can be responsible for four "electrokinetic phenomena" in systems such as the soil-water electrolyte system where charged particles are balanced by mobile counter charges (Mitchell, 1993). Each involves relative movements of electricity, charged surfaces, and liquid phases, as show schematically in Fig. 2.3. This technique has been used for:

- improving stability of excavations (Chappell, et al. 1975),
- stabilization of fine grained soils (Mitchell, et al. 1977),
- removal of metallic objects from the ocean bottom (Esrig et al. l966),
- decreasing pile penetration resistance (Begeman, 1953; Thompson, 1971),
- increasing petroleum production (Amba, et al. 1964),
- determination of volume change and consolidation characteristics of soils (Banerjee, et al. 1980),
- separation and filtration of materials in soils and solutions (Yukawa, et al. 1971),
- stabilization of slopes, embankments and dams (Casagrande 1952, 1962 & 1983, Gladwell 1965, Fetzer, 1967, Long and George 1967),
- Strengthening subgrades and sub-bases under pavement (Simon, et al. 1956, Dearstyne and Newman 1963, Gladwell *1965),*
- Injection of bentonite suspension into low permeability mils (Holmes l963), etc.

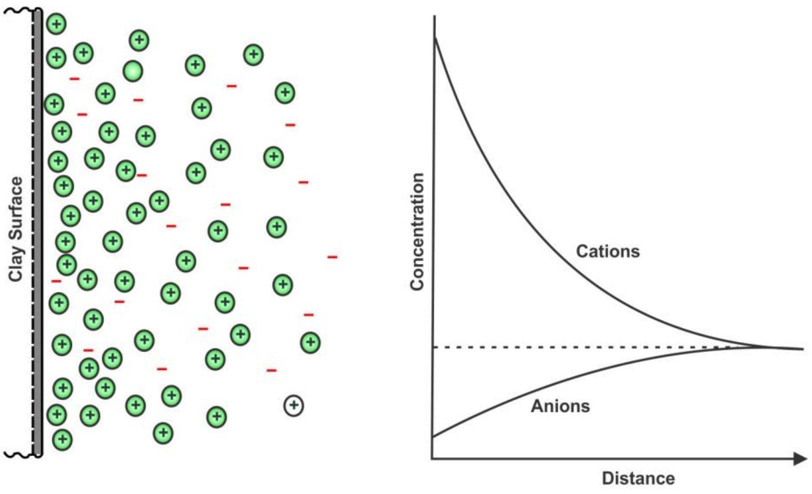


Fig. 2.2 Distribution of ions adjacent to a clay surface (Mitchel, 1993)

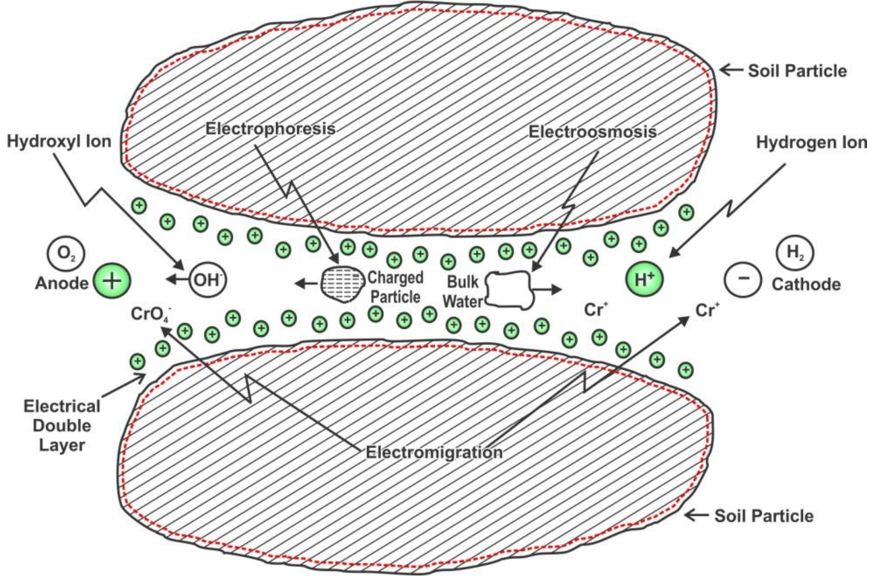


Fig. 2.3 Movement of ions and charge between soil particles (Mitchel, 1993)

2.1.1 Electrokinetic Phenomena

When a DC electrical current or voltage is applied across a saturated soil specimen, along with chemical and hydraulic gradients, positive ions are attracted to the negatively charged cathode and negative ions move to the positively charged anode. The direction and quantity of contaminant movement is influenced by the contaminant concentration, soil type and structure, and the mobility of contaminant ions, as well as the interfacial chemistry and the conductivity of the soil pore water (Virkutyte et.al. 2002).

2.1.2 Contaminant Migration

The process of contaminant migration takes place by adsorption and desorption. Adsorption is generally defined as the formation of a layer(s) of gas, liquid, or solid on the surface of a solid. It can be seen as a partitioning or distribution of the solute between the aqueous phase and the solid phase. Depending on the nature of forces involved, adsorption can be classified into physi-sorption and chemi-sorption. With chemi-sorption, single layers of molecules, atoms or ions are attached to the adsorbent surface by chemical bonding. In contrast, physisorption involves weak Van Der Waals forces that hold the adsorbed molecules to the adsorbent surface. Desorption is the reverse process of adsorption and involves the removal of contaminants from the soil surface. During desorption, the ions, atoms or molecules are detached from the soil surface. The rate at which desorption takes place is much slower than the adsorption rate. Also, desorption of contaminants generally takes place at lower pH values than adsorption. During electrokinetic soil remediation, the acidic front advances through the soil, reducing the pH, this reduction in pH aids in desorption of metals from the soil surface.

Previous research showed that the principal contaminant migration mechanisms that occur during the electrokinetic remediation process are electroosmosis, electromigration, diffusion and electrophoresis (Acar and Alshawabkeh, 1993; Probstein and Hicks, 1993, Virkutyte el. al. 2002). Among them, the two mechanisms, electroosmosis and electromigration are the primary driving forces to extract contaminants from electrokinetic remediation process (Acar et. al. 1990, Alshawabkeh and Acar, 1992). Electroosmotic advection can purge ionic and non-ionic species through soil mainly towards the cathode. This is perhaps best achieved when the state of materials (dissolved, suspended, emulsified, etc.) are suitable for the flowing water to carry them through the soil pore (Chung and Kang, 1999). Electroosmosis is more effective for the removal of cationic contaminants than for anionic contaminants. On the other hand, electromigration is of great significance for both anionic and cationic contaminants. Acar and Alshawabkeh (1993) evaluated the relative contribution of electroosmosis and electromigration on cationic contaminant migration and concluded that the effects of electromigration can be greater than those of electroosmosis in this respect. However, Gray and Mitchell (1993) reported that electroosmosis contributed a significant percentage to the overall migration of cations, at least when the cation concentrations were low. The effect of electroosmosis and the significance of electromigration on anionic contaminants such as Cr(VI), As(V), As(III) are not reported in literature. Besides the above two phenomena, diffusion plays a relatively constant and often insignificant role in both cationic and anionic contaminant transport (Acar and Alshawabkeh, 1993; Shackelfor, and Daniel, 1991). Electrophoresis, which refers to the transport of charged particles under the influence of an electric current, can be an important mechanism for sludges, but it is not significant for contaminant transport in soils (Pamukcu S. and Wittle, 1992).

The dominant and most important electron transfer reactions that occur at electrodes during electrokinetic process are the electrolysis of water (Probstein et. al. 1993; Acar and Alshawabkeh 1993). The oxygen gas generated at the anode and the hydrogen gas generated at the cathode are allowed to escape out of the soil. The acid front (H^+) is carried towards the cathode by the electrical migration, diffusion and advection. The hydrogen ions produced decrease the pH near the anode. At the same time, an increase in the hydroxide ion concentration causes an increase in the pH near the cathode (**Fig. 2.4**). The OH^- ion generated at the cathode also has a tendency to migrate towards the opposite electrode, anode. The extent of migration depends on the buffering capacity of the soil. In a soil with low buffering capacity, a distinct pH gradient ranging from 2 near the anode and to 12 near the cathode is generally developed (Michael Harbottle, 2003).

In order to solubilize the metal hydroxides and carbonated formed or different species adsorbed onto soil particles, as well as protonate organic functional groups, there is a necessity to introduce acid into the soil. However, this acid addition has some major drawbacks, which greatly influence the efficiency of the treatment process. The addition of acid leads to heavy acidification of the contaminated soil, and there is no well established method of determining the time required for the system to regain equilibrium.

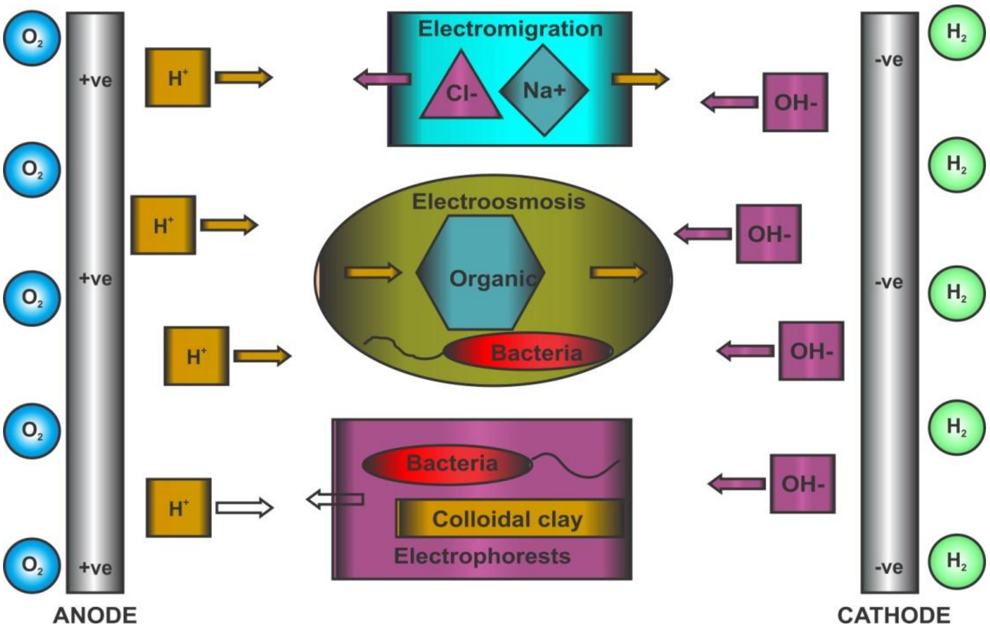


Fig 2.4 Electrode Reactions at Anode and Cathode (Michael Harbottle, 2003)

Adsorption onto the electrode may also be feasible, as some ionic species will change their valency near the electrode depending on the soil pH, making them more likely to adsorb. (Van Cauwenberghe, 1997). Once the remediation process is over, extraction and removal of heavy metal contaminants are accomplished by electroplating at the electrode, precipitation or co-precipitation at the electrode, pumping water near the electrode, or complexing with ion exchange resins (Virkutyte et. al. 2002).

2.1.3 Application of Electrokinetics

- **Electrokinetic Extraction/ Injection:** In recent years, a major portion of geo-environmental engineering research has been devoted to electrokinetic extraction/injection, which includes removal of contaminants, heavy metals, and radionuclides from subsurface soil. Acar et. al. (1992, 1993) have demonstrated that hazardous metals like lead and cadmium could be successfully removed from soil using electrokinetics. Work is going on for electrokinetic removal of uranium from contaminated soil. In Russia, electrokinetics is already in use to remediate uranium contaminated soil (Yeung and Subbaraju, 1995). Thevanayagam and Rishindran

(1998) showed that it is possible to inject nitrate and other nutrients into clayey soils and aid/enhance remediation processes in such soils.

- **Dewatering and Consolidation:** It is extremely difficult to use conventional methods of dewatering in clayey soil, as the pore size is very small. Electroosmotic flow is an attractive method of dewatering clayey soils and suspensions as it is relatively insensitive to pore size and pore size distribution. Due to electroosmosis, the water flows towards the cathode, where it is drained away. If in this process, no water is allowed to enter at the anode, then consolidation of soil also occurs. (Lamont-Black, J. et. al., 2006, 2008)

- **Electrokinetic Barrier and Fencing:** A continuous or periodic electrical gradient applied across a compacted clay liner could reverse the hydraulic flow induced by sustained hydraulic head and to halt the migration of organic and inorganic contaminants into the environment. Similarly, an electrokinetic barrier may be installed across a slurry wall encapsulating hazardous waste to mitigate contaminate migration. (Hazardous and Solid Waste Amendments (HSWA),1984)

- **Ground water Purification:** Electromigration offers the potential for purification of ground water contaminated with highly soluble compounds, such as Na^+, Cl^-, NO^{3-}, SO_4^{2-}. A field experiment to test the efficacy of electromigration for pre-concentrating dissolved SO_4^{2-} in ground water associated with fossil fuel power plant that was conduction by Patterson and Runnels (1996) showed success.

- **Bioelectrokinetics:** Bioparticles like pro and eukaryotic cells have overall negative charges and proteins have either negative or positive charge at neutral pH. When a DC electric field is applied to a system consisting of a bioparticle suspended in an aqueous medium, the particle will move due to electrophoresis phenomena. If the charge of the particle is Q in the electric field of E, the charged particle experiences a force QE, which results in moving the particle (Wick et al. 2007; Lee et al. 2009a, Keun-Young Lee, et. al., 2011).

2.2 LABORATORY INVESTIGATIONS FOR ELECTROKINETIC REMEDIATION

In the late 1980's and early 1990's, several bench-scale studies were conducted (Hamed et al. (1991), Pamuku and Wittle (1992), Acar and Alshawabkeh (1994), Reed et al. (1996), Reddy and Parapudi (1997a). These studies validated the potential application of electrokinetics to treat soil contaminated with metals. Tests were done on different soil types with varying buffering capacities. The removal efficiencies were dependent on the soil type and properties, type of metal ion, current or voltage applied, type of electrode, etc. The removal of the metals from the soils was mainly attributed to electromigration and electroosmosis. Depending on the pH of the soil medium, concentration, and type of ions, either electromigration or electroosmosis dominated the metal removal rates. From the laboratory-scale tests performed by the above mentioned researchers, it is clear that the pH front advanced from the anode towards the cathode. The pH front generated aids in desorption of metal ions. Once desorbed, metal ions can then be transported to the corresponding electrodes of opposite sign. However, the high pH zone generated at the cathode may precipitate the metals migrating to the cathode. This reduces the metal solubility and plugs the soil resulting in reduced metal removal efficiency.

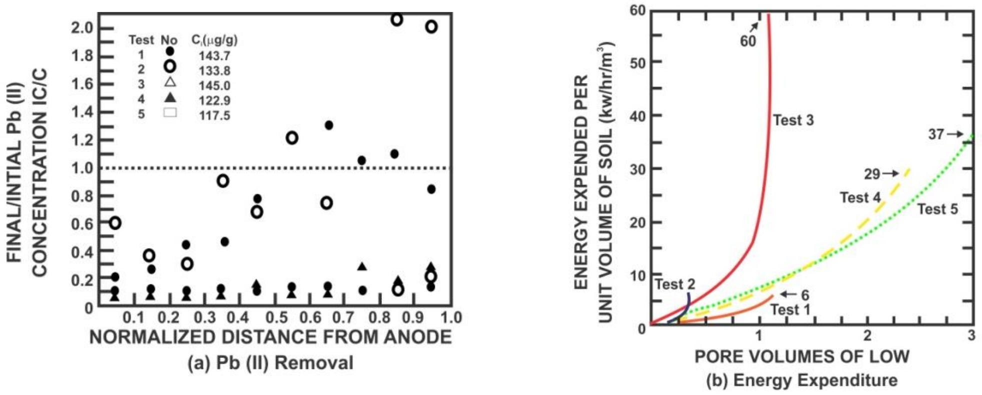
To overcome the problem of high pH and adsorption of contaminants near the cathode, researchers have developed several techniques. Several researchers investigated the use of amendments at the electrodes Reed et al. (1995), Yeung et al. (1996), Cox et al. (1996), Wong et. al. (1997), Yang et al. (1998), Chung and Kang (1999), Reddy et al. (2003), Sawada et al. (2003). The uses of different amendments such as acetic acid, hydrochloric acid, humic acid, ethylene diamine tetraacetic acid (EDTA), citric acid, nitric acid, potassium iodide etc., was investigated. These chemicals were used either to neutralize the basic front produced at the cathode or used as complexing agents. Complexing agents desorb the contaminants by forming soluble complexes that can be easily transported out of the soil. Several researchers have developed innovative methods in an effort to overcome the problem of high pH and adsorption of contaminants onto the soil. Li et al. (1996, 1997) developed an alternative to the currently used electrokinetic soil-remediation technologies to deal with the pH impact on treatment efficiency. Instead of being directly placed in the soil, the cathode was connected to the soil by a conductive solution. In this way, the base front produced at the cathode enters the inserted electrode solution first, and the front advances towards the soil until it meets the acid front. If the length of the conduction solution is appropriate, the base front cannot reach the soil. Hence, the positively changed heavy metal contaminants transport from the soil before being precipitated as hydroxides. Using this method, metals such as Cu, Zn, Cr, Cd, and Pb have been successfully removed from artificially contaminated soils. Li also demonstrated that the heavy metals such as Zn, Cu, Cr, Cd, and Pb could be removed from naturally contaminated sand. Removal efficiencies higher than 90% have been achieved by placing a conductive solution between the cathode and the soil being treated.. Li and Li (1998) also developed a method that prevented the precipitation of metals in the soil close to the cathode. A cation-selective membrane was placed between the soil and the cathode. This membrane would stop the advancement of hydroxyl ions into the soil. Tests conducted on copper-contaminated sand indicated that removal efficiencies higher than 90% could be achieved.

Maini et al. (2000) investigated the remediation of metal-contaminated soil by the combination of bioleaching and electrokinetics. Preliminary partial acidification was performed on copper contaminated soil by amending it with sulphur oxidizing bacteria. The soil was then incubated at constant moisture and temperature for 90 days, thereby acidifying the soil from pH 8.1 to 5.4 biologically. Later this soil was treated with electrokinetics, yielding 86% copper removal in 16 days. Pre-acidification by sulphur-oxidizing bacteria increased the cost effectiveness of the electrokinetic treatment reducing the power requirement by 66%. Li et al. (2000) developed an integrated electrokinetic system that enhances the removal of heavy metals from soils.

The system consisted of a layer that was continuously flushed with nitric acid at pH 3 near the cathode region, which reduced the effect of OH^- ions. A 0.4 M NaOAc at pH 3.8 and acetic acid at pH 4.0 solutions flushed the anode and cathode reservoirs, respectively. The NaOAc used in the anode increased the total number of H^+ ions in the soil which assisted in dissolving the metals, resulting in increased solubility. Tests were conducted using kaolinite and carbonate-rich illitic soils, contaminated with lead. These results indicated that over 80% lead removal efficiencies could be achieved. Research on laboratory scale electrokinetic remediation was performed using various types of soil types. Different soils like kaolinite, momtmorillonite, illite, silt, sand, etc., have been used. However, kaolinite was the soil that was investigated in most cases. The soil type has been found to have an effect on the metal removal efficiencies. Also, the investigation was performed on spiked soils rather than the actual contaminated soils. The removal of various metals like lead, cadmium, chromium, copper, zinc, nickel, and strontium from soil were investigated. Wide ranges of concentrations varying from 30 to 17,950 mg/kg of metals were investigated. The removal efficiencies of the soils contaminated with low initial concentrations were low compared to high initial metal concentrations. Also lead was the most widely investigated metal, although, other metals were also studied. It is interesting to note that the removal efficiencies of lead from these soils was found to be low compared to other metals.

There have been a number of studies which investigated the removal of metals from contaminated soils. However, none of the studies investigated the effects of ionic valence and size on their movement. Hamnett (1980) was the only researcher who investigated the effect of size on movement of ions under an electrical field. Hamnett evaluated the electromigration of ions of different salts and found that smaller ions (i.e., Na) were more mobile than larger ions (i.e., K, Ca, Ni). (Wise and Trantolo, 1994). Hence the study presented in this report was undertaken to investigate and compare the movement of ions based on charge and size.

A comprehensive subsequent study on removal of Pb(II) from kaolinite is reported by Hamed et al. (1991). Kaolinite specimens were loaded with Pb(II) at 118 to 145μg/g of dry kaolinite, below the cation exchange capacity of this mineral, electroosmosis removed 75% to 95% of lead across the test specimens (Fig. 2.5). The study clearly demonstrated that the removal was caused by migration and advection of the acid front generated at the anode by the primary electrolysis reaction.



(a) Pb (II) Removal

(b) Energy Expenditure

Fig. 2.5 Pb(II) removal from kaolinite and corresponding energy expenditure

A laboratory program was undertaken by Pamukcu and Wittle (1994) to investigate the feasibility of electrokinetic treatment of clay mixtures containing different metals and surrogate radionuclides such as: As, Cd, Hg, Pb, Co, Cs, Sr, U and several types of anions and chlorinated hydrocarbons. Five soil types were studied: kaolinite soil with distilled water, Na-montmorillonite clay with distilled water (MS), sand with 10% Na-montmorillonite clay with distilled water (SS), kaolinite with simulated groundwater (KG), and kaolinite clay with humic substance solution (KH). The tests were conducted under a constant potential of 30V direct current on specimens 3.56 cm diameter and 7.62cm long. The termination time was varied from 24 hours to upto 48 hours. For a number of extended hours of treatment, the electrode chambers (both anode and cathode) were drained approximately 24 hours and refilled with appropriate pore water used in the soil specimen. This practise, however, did not increase the contaminant removal or water flow rate.

The analysis of results showed the metal removal success was upto 99% for the duration of treatment that did not exceed 50 hours. It should be noted that, metal removals were calculated at the location of lowest concentration. However, the transported metals mostly were accumulated close to the cathode end. Table 2.1 summarizes the contaminant removal percentage as well as the cumulative fraction of pore volume of water transported through specimens after electrokinetic treatment of four heavy metals. The study showed that the variation in the concentration reduction percentage appears to depend on the soil matrix, the metal, and the pore fluid type. It appears to have little or no correlation with the volume of flow achieved during treatment.

Another set of test was carried out in this study to investigate the effect of rate of initial concentration on percentage of removal of cadmium. Fig. 2.6 and 2.7 illustrate the concentration profiles of Cd across the soil specimen based on the quantitative measurement made at three axial locations in the specimens for low and high initial concentration of Cd in soil. It can be seen that the lower concentration metal mixed soils did not show as high percentage of removal as those of the high concentration metal specimens for the same duration of treatment. The average removal of Cd in the first half of the soil cylinder was computed to be 16.5% for the low concentration case, whereas this was 84% for the high concentration case. At low concentration of metal, the current carried by the clay surface constituted a larger portion of the total current and resulted in larger net flow of water in the cathode direction. At high concentration of the metal, the current was easier to pass through, because the bulk of it would be carried with present metal ions through the pore space. As a result, electroosmosis appears to be the dominant mechanism of electrokinetic extraction of contaminants when they are present at low concentrations. In this condition, most of the chemical present might be absorbed onto the solid phase and, therefore, may not be easily removed by the electroosmotic flow only.

Table 2.1 Removal percentages of metals and pore volume of water transported towards cathode chamber (Pamukcu and Wittle 1994)

Metal	Exp. No. 1		Exp. No. 2		Exp. No. 3		Exp. No. 4		Exp. No. 5	
	% Rem*	PV^b	% Rem*	PV^b	% Rem*	PV^b	% Rem*	PV^b	% Rem*	PV^b
Cr	93	0.18	97	0.15	95	0.23	95	0.12	97	0.12
Cs	72	0.65	74	0.3	77	0.64	55	0.96	89	0.3
Sr	98	0.41	96	0.88	99	0.44	92	0.53	99	0.63
U	79	0.35	70	0.69	85	0.25	44	0.77	33	0.64

% Rem*: Percent Removal at the location of lowest concentration achieved.

PV^b: Pore volume of water transported to the cathode chamber during treatment.

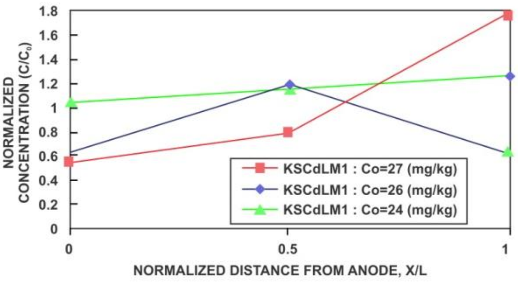


Fig. 2.6 Normalized concentration variation of cadmium from anode to cathode (low concentration) (Pamukcu and Wittle 1994)

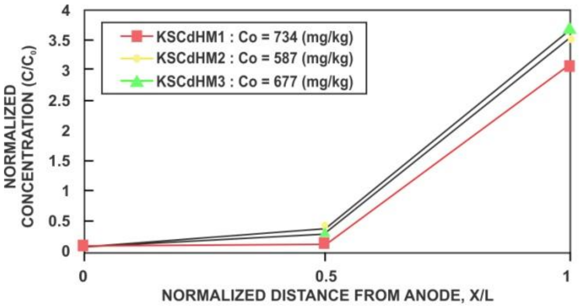
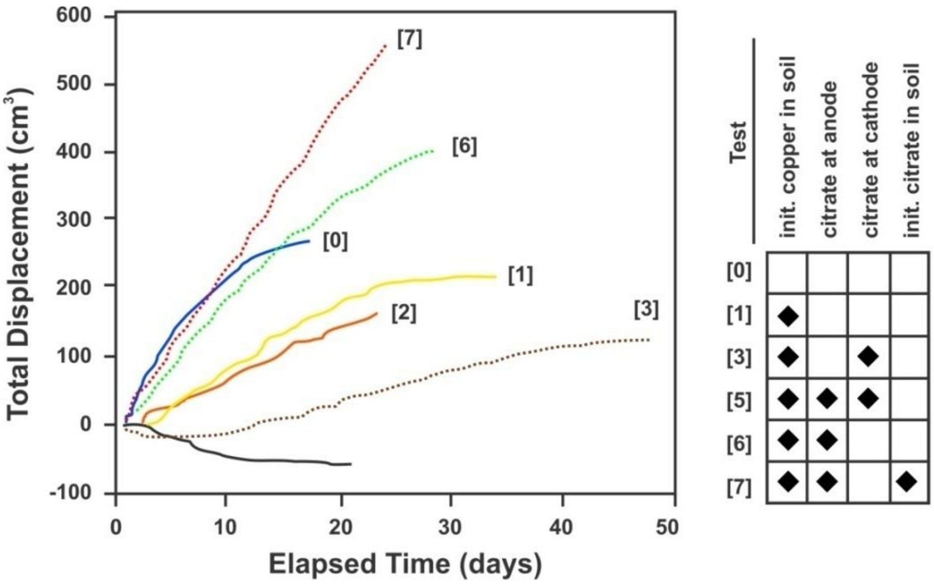


Fig. 2.7 Normalized concentration variation of cadmium from anode to cathode (high concentration) (Pamukce and Wittle 1994)

A set of one dimensional electrokinetic experiments were performed on Georgia kaolinite clay by Kykholt (1992), to identify may of the complex driving features of the electrokinetic treatment of contaminated soils with copper. Stock electrolyte solutions were prepared from analytical grade reagents and deionised distilled water, and stored in polyethylene bottle at room temperature. Various electrolyte solutions were mixed with dry kaolinite and different treatments were applied at the reservoirs. Mixtures of copper and sodium nitrates and sodium citrate in various concentrations were used as reservoirs and soil electrolyte solutions. Copper nitrate solutions were acidified slightly with 1.5% HNO_3 such that the pH was held below 4.5 to reduce copper adsorption. Kaolinite samples were prepared with an electrolyte solution at water content around 43% and hydraulic conductivity was 3.5 x 10^{-7} cm/s. The goal of each chemical treatment scheme was to enhance electrokinetic migration of copper through the soil to the cathode reservoir, preferably by increasing the electroosmotic flow rate while simultaneously enhancing the copper in the pore solution (particularly near the cathode). For instance, citrate was added because it is known as an excellent extraction and complexation agent for copper. In each case, however, a strongly alkaline pH persisted in the zone of soil nearest to the cathode, rendering the copper immobile.

The most significant impact of the various chemical treatment schemes was on the electroosmotic flow. Electroosmotic flow in kaolinite varied significantly under the various reservoir and soil chemical treatment schemes. A summary of the records of electroosmotic displacement for several of the electrokinetic tests is shown in Fig. 2.8. The first of the tests, was a control test performed on kaolinite that was free of copper. The flow rate increased over the first day from 0 to 32ml/day. This remained constant over the next two days, but then fell in an exponential fashion to a flow rate of 10ml/day at 15 days. For test in which kaolinite was prepared with copper and without citrate, the flow was much less than that of other cases. For instance, the flow rate for test 1 was nearly zero initially, roughly 10ml/day (Ke = 3.3 X 10^{-5} cm^2/Vs), for the period of 20 days, and near zero at 30 days. The flow for these tests was typically lower, even negative, during the early stage of testing for these cases. The only exception was in Test 6, in which citrate was added solely to the anode reservoir. The flow response for this test was roughly equivalent to the case without copper. The flow was greatest for the test with initial copper and citrate solution in soil, and citrate treatment at the anode, i.e., Test 7.



Test	init. copper in soil	citrate at anode	citrate at cathode	init. citrate in soil
[0]				
[1]	◆			
[3]	◆		◆	
[5]	◆	◆	◆	
[6]	◆	◆		
[7]	◆	◆		◆

Fig. 2.8 Sensitivity of various treatment schemes on the electroosmosis (Eykholt 1992)

In this research one extreme effort was attempted to mobilize the copper that had accumulated near the cathode end by the sudden addition of strong acid to the cathode reservoir. Records of the reservoir pH and electroosmotic flow for Test 2 are shown in

Fig. 2.9. At the elapsed time of 23 days, 30ml of 0.2N HNO_3 (nitric acid) were added to the cathode reservoir. The most significant effect of acid treatment was that the electroosmotic flow suddenly reversed directions toward the anode. The average flow rates before and after the additions were 7.0 ml/day and 10.4 ml/day, respectively. While the pH of the cathode was re-established to previous levels within five days, the flow toward the anode persisted. This observation affirms the assumption that chemical changes near the cathode may have the greatest effect on electroosmotic flow.

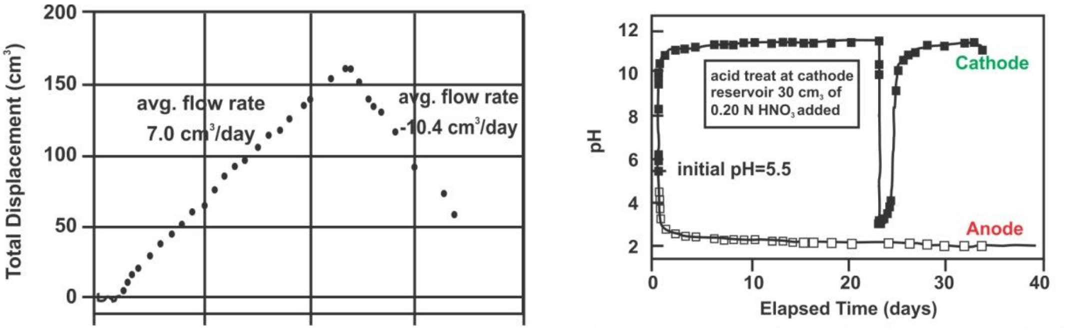


Fig. 2.9 Effect of acid treatment in the cathode reservoir (Eykholt 1992)

To study removal of cadmium from saturated kaolinite, four 1D electrokinetic remediation tests were conducted by Acar et. al (1994). Direct constant current equal to 3 mA was applied across the specimens with 10.2 cm in both diameter and length, with initial cadmium concentration of 99 – 114 μg/g. Tests continued between 716 to 1027 hours and resulted in 0.27 to 3.98 pore volumes of flow in different tests. The results indicated that the flow was substantially higher in the higher pH specimen and lower in lower pH specimen (Fig. 2.10). Fig. 2.11 presents the change in the electroosmotic coefficient of permeability (ke) with time during the process from 1 x 10-4 cm2/Vs to less than 1 x 10-6 cm2/Vs. These results demonstrate that ke is not constant for one soil and decrease during the process due to the formation and introduction of the electrolysis products at the electrode chambers and the changing chemistry across the soil mass. All tests conducted on kaolinite loaded with cadmium showed 92 – 100% removal of cadmium across the cell, except in the last section very close to the cathode. It is concluded from this study that power expenditure is strongly affected by the low – conductivity zone close to the cathode. Precipitation of cadmium in this zone may increase the electrical potential difference and power expenditure (Fig. 2.12).

R. Shrestha, R. Fischer & M. Sillanpaa (2007) studied the mobilization and accumulation of Cr at the sediment water interface in an electric field at varying different positions and conditions of the electrode arrangement. The tests were carried out with a natural sediment containing heavy metals, with experiments being performed in columns filled with sediment using electrodes made of conductive polymers (polyethylene with carbon black) at a maximum current density of 0.5 mA/cm^2. The experimental results suggested that mobilization and accumulation of Cr depended highly on chemical factors like pH value, redox potential, respectively redox status and the content of Fe, Al and organic matter in the soil or sediment. The sorption of Cr (III, VI) was very high in the pH range > 4.5. A high mobilization of Cr (III, VI) was seen in the case of the experiments with the anode at the sediment, because the pH value was lower than mentioned above. On the opposite, the best condition for the Cr (III, VI) immobilization is high pH values (cathode at the sediment).

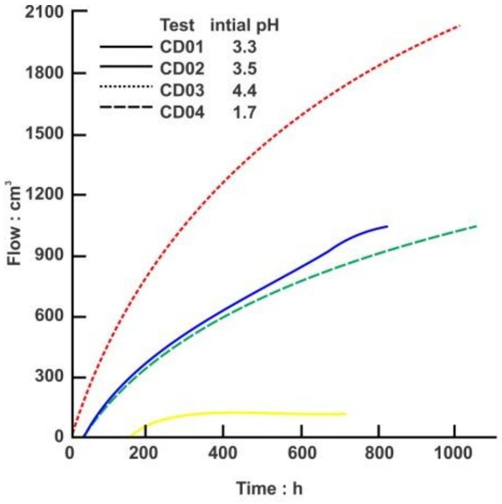


Fig. 2.10 Development of flow quantity with time (Acar et. al. 1994)

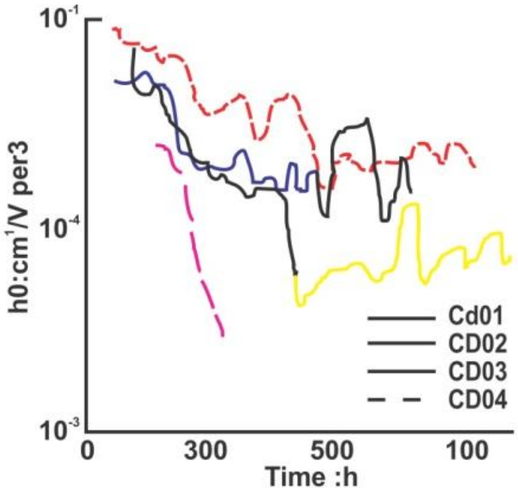


Fig. 2.11 Development of electroosmotic coefficient permeability K_e (Acar et. al. 1994)

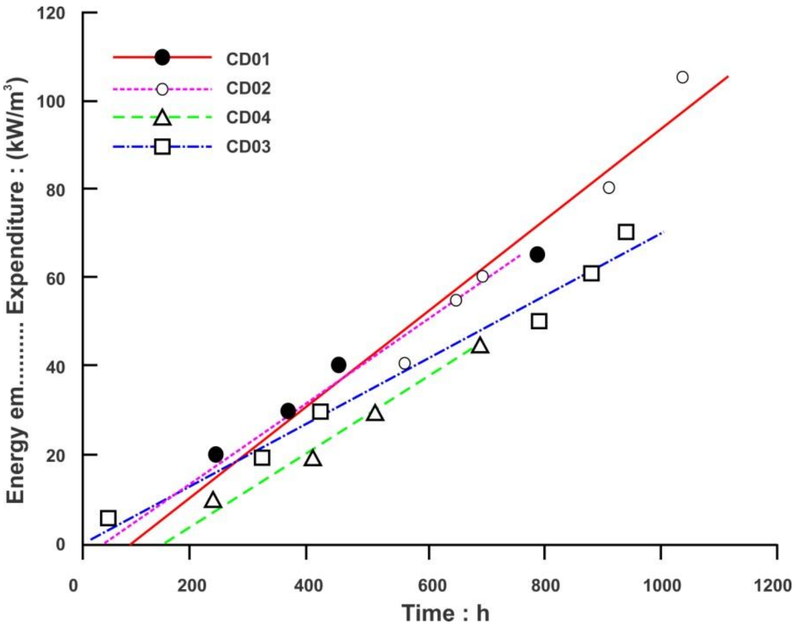


Fig. 2.12 Energy expenditure (Acar et. al., 1994)

M Saleem, M. H Chakrabarti et. Al. (2011) studied electrokinetic remediation of nickel from low permeability soil using titanium electrodes having inter-electrode spacing of 10 cm. They concluded that efficiency improved from 49.3% to 57.2% when the current density was increased from 4.36 mA/cm^2 to 13.1 mA/cm^2. Furthermore, an enhancement in efficiency from 38.5% to 54.3% was observed when voltage gradient increased from 1 V/cm to 2 V/cm (at 13.1 mA/cm^2). Further increase in voltage gradient to 2.5 V/cm improved efficiency during initial runs. An overall reduction of 3.2% was observed after 60 h of operation in comparison to that obtained at 2 V/cm, being attributed to precipitation and localized accumulation of metallic ions. An inverse relationship between efficiency and electrolyte pH was also observed (at 13.1 mA/cm^2 and 2 V/cm). Although a removal of 74.1% was achieved at pH = 4.5, the system required optimization as the nickel content in treated soil was above the maximum values.

Hyo Sang Lee, Sung Hwan Ko, et. al. (2003) applied electrokinetic remediation for removal of heavy metals from mine tailing soils of two abandoned mines with Cu, Pb, Cd, As and Zn as major contaminants. Since tailing soils had a net positive zeta potential, electroosmotic flow formed towards the anode, thus about 15-34% of removed metals were found in anode chamber, implifying that the mechanism of metal removal were by electromigration mostly and in minority due to electroosmosis. The use of citric acid as an electrolyte enabled maintenance of and acidic pH with low buffering capacity, which in turn resulted in increase electroosmotic flow rate and higher metal removal efficiency. Without this addition a steep pH gradient would develop greatly diminishing the electroosmotic flow rate. They observed an overall 37 – 41% removal in 2 weeks under application of 0.25mA/cm^2 current density and using 2.5mS/cm conductivity electrolytes.

K. R. Reddy, Kranti Maturi et. al. (2009) carried out study on sequential remediation of mixed contaminants on kaolin soil. The selected contaminants included phenanthrene and nickel to simulate field mixed contaminants. The sequential electrokinetic process included the use of citric acid followed by either Tween 80 or Igepal. Most of the nickel migrated from the anode to the cathode in the tests; however, it precipitated in the section close to it i.e. cathode due to the high pH. Conversely, they observed an removal efficiency of 96% and 88% in test with citric acid followed by Igepal and citric acid followed by Tween 80, but could not achieve appreciable migration and removal of phenanthrene in both of these tests. An overview of previous studies on laboratory-scale is provided in Table 2.2.

Table 2.2 Laboratory Electrokinetic Investigations

Investigator	Contaminants (Concentration)	Type of Soil	Current/ Voltage	Treatment Efficiency	Remarks
Hamed et al., (1991)	Pb (118-145 mg/kg)	Kaolinite	0.037 mA/cm^2	75-95 %	Showed that the flow in electroosmosis is time dependent and is strongly influenced by the electrochemistry resulting from the pH gradients.
Pamuku and Wittle, (1992)	Cd (666-748 mg/kg), Co (550-1020 mg/kg), Ni (395-1084 mg/kg), and Sr (463-686 mg/kg)	Montmorillonite, kaolinite, Clayey sand, and Clay	3.93 v/cm	85-95 %	Efficiency of electrokinetic water flow exhibited by different soils in the decreasing order is kaolinite > Clayey sand > Na-montmorillonite.
Acar et al., (1994)	Cd (99-114 mg/kg)	Kaolinite	N/A	90-95 %	No enhancement techniques used, heavy metal accumulated at the cathode
Reed et al., (1995)	Pb	Natural Soil	8 v/cm	50-95 %	Chemical conditioning (Acetic acid, hydrochloric acid, or EDTA) in cathode reservoir. Conditioning improved removal efficiency to a great extent.
Reed et al., (1996)	Pb (150 and 1000 mg/kg)	Field Soil	3.75 and 7.5 v/cm	N/A	Increase in voltage resulted in increased remediation efficiencies and soil with low initial Pb concentrations was difficult to treat.
Yeung et al., (1996)	Pb (1600 mg/kg)	Natural Kaolinite + 4.3 % Iron oxide.	3.15 & 1.57v/cm	90 %	The use of EDTA as a complexing agent improved the removal efficiency
Cox et al., (1996)	Hg (500 mg/kg)	Loam soil	0.38 – 0.538 ma/cm^2	Upto 99 %	Enhancement agents (Iodine/Iodine Lixiviant) were used
Puppala et al., (1997)	Pb (2330 & 17950 mg/kg)	Synthetic soil representing illitic deposit	0.05 & 0.25 ma/cm^2	N/A	Acetic acid as an enhancement agent and ion selective to prevent back transport
Reddy et al., (1997a)	Cr (VI) (500mg/kg)	Glacial till, kaolin, and Na-montmorillonite	1.3 v/cm	N/A	Effect of soil composition showed that Cr (VI) removal was higher in glacial till which has high buffering capacity than the other two soils.
Reddy and Parupudi, (1997b)	Cr (VI) (500 mg/kg), Ni (500 mg/kg), Cd (250&500 mg/kg)	Kaolinite and Glacial till	1.3v/cm	N/A	Electrokinetic migration of Cr (VI) is more significant whereas Ni and Cd movement is less in high buffering capacity soils (Glacial till)

Table 2.2 Laboratory scale electrokinetic investigations (Cont’d)

Investigator	Contaminants (Concentration)	Type of Soil	Current/ Voltage	Treatment Efficiency	Remarks
Wong et al., (1997)	Pb (358 & 715 mg/l), Zn (113 mg/l)	Fine Sand	1.5 v/cm	68- 100 %	The use of EDTA as a complexing agent improved the removal efficiency
Li et al., (1997)	Cr (30.5 mg/kg), Cu (48.9 mg/kg)	Loam	1.0 v/cm	> 90 %	Conductive solution was placed between cathode and the soil being treated.
Yang and Lin, (1998)	Pb (1000 mg/kg)	Silt loam	1.0 v/cm	11-53 %	Citric acid was a better amendment than acetic acid and EDTA
Chung and Kang, (1999)	Pb (5000 mg/kg)	Marine Clay	0.06, 0.636, & 1.273 ma/ sq.cm.	35- 94 %	The use of amendments such as nitric acid, ethylenediamine, and acetic acid used were found to be efficient in removing lead.
Maini et al., (2000)	Cu (1000 mg/kg)	Silt Soil	3.72 a/m^2	86 %	Bioleaching with Sulphur reducing bacteria and electrokinetics were sequentially combined.
Li and Li, (2000)	Pb (1000 & 5000 mg/kg)	Kaolinite, Illite	0.11 & 0.022 ma/sq.cm.	>80 %	Integrated EK system consisting a layer that was continuously flushed with nitric acid at cathode was used
Sah and Lin, (2000)	Cu (490-530 mg/kg)	Clay, Silt clay, Silt clay loam	N/A	70-85 %	Highest removal efficiency was found in acidic clayey soil mixed with hydrochloric acid.
Sawada et al., (2003)	Cu	Kaolinite	2.2 v/cm	N/A	Humic acid when used as an amendment increased the Cu removal rate by three times.
Reddy et al., (2003a)	Hg (500 mg/kg)	Kaolin, Glacial Till	1.0 v/cm	77, 97 %	Potassium Iodide was used as an amendment
Reddy & Chintamreddy, (2003b)	Cr(VI) (1000 mg/kg), Ni (500 mg/kg), Cd (250 mg/kg)	Kaolinite	1 v/cm	68-94 %	Sequential electrokinetic extraction was tested with citric acid and sodium hydroxide as amendments
Chou et al., (2004)	Cd, Pb (100 mg/kg)	Silt clay	1 v/cm	54-99 %	Best removal efficiencies were achieved when buffering solutions were used at the anode and cathode reservoirs.

2.3 FIELD DEMONSTRATIONS FOR ELECTROKINETIC REMEDIATION

Several field scale electrokinetic demonstrations have also been conducted (U.S. EPA (1997b), Lageman (1993), Gent et al. (2004)), though well documented field applications are limited. An overview of the field scale demonstrations is presented in Table 2.3, performed on different soils with different contaminants, with uranium contaminated sites showing best removal efficiencies. Amendments like citric acid, carbonate salts, and acetic acid were used during treatment of the uranium-contaminated site. Gent et al. (2004) evaluated the extraction of chromium and cadmium from contaminated soil using bench and field scale tests, the results indicated field scale demonstration to be more effective than laboratory scale tests for contaminant removal.

Lageman (1993) reported the results of five field experiments and projects on electrokinetic remediation, conducted in Netherlands, with removal of lead, copper, arsenic and cadmium in range of 70% to 80% have been reported. Banerjee (1994) reported results of a field study at a superfund site at Corvallis, Oregon, undertaken in order to investigate the potential of electrokinetic remediation technique by itself or in combination with pump and treat method. The onsite soils, the groundwater in the upper aquifer and the surface water were heavily contaminated with inorganic contaminants, such as arsenic, barium, chromium, copper, iron and lead present in concentration in excess of the primary drinking water standards. The treatment procedures explored in these experiments included: (a) extraction of contaminants by continuous pumping (b) continuous electrokientic treatment and pumping combined and (c) electrokientic treatment with occasional withdrawal of effluents. In order to assess the effectiveness of the combined treatment schemes, the mass of chromium removed per well volume of effluent withdrawn were computed from the results of each experiment. The total mass of chromium recovered per well volume of effluents by pumping, combination of electrokinetics with continuous pumping, and combination of electrokinetics with occasional pumping were approximately, 4.77gm, 5.15gm and 9.23gm respectively. Table 2.4 presents a brief explanation of available field data for electrokientic remediation.

Three pilot scale tests were carried out by Acar and Alshawabkeh (1996), to investigate the feasibility and efficiency of removing lead with electrokientic treatment. A constant direct current density of 133 mA/cm^2 was applied. Subsequent to 2950hr of processing and an energy expenditure of 700kWh/m^3, 75% of the lead removed across the soil was found to be precipitated within the last 2 cm close to the cathode and the geofabric separating the soil from the cathode compartment; 15% was left in the soil before reaching this zone and 10% was unaccounted for. Almost no lead was found in the catholyte and on the cathode.

Table 2.3 Electokinetic pilot or field scale demonstrations (all values are in ppm)

Developer	Soil Type(s)	Electrode Spacing	Electrode Depth	Voltage/ Current	Processing Fluid	Remediation Area	Contaminant Treated	Time Duration	% Removal Efficiencies	Cost
Geokinetics International, Inc. (GII)-Pool Process	Clay	5 – 10 feet	0.3 – 3.3 feet	5 – 20 volts 0.5 - 1.0 amperes	Acid or alkali	230 feet by 10 feet Depth of 3.3 feet	Arsenic (As), Cadmium (Cd), Chromium (Cr), Copper (Cu), Lead (Pb), Nickel (Ni), Zinc (Zn)	2 – 8 months	***Before*** Cd: 660, Cu: 500-1000, Ni: 860, Pb: 300 - 5000, Zn: 2600 ***After*** Cd: <50, Cu: <250, Ni: <80, Pb: <75, Zn: <300	$300-$500* per cubic yard *Total cost
Texas A&M University	Kaolinite, saturated silty clay	N/A	15 feet	N/A	Sodium Cholride	700 to 1000 cubic feet depth of 15 feet	Uranium, Chromium	4 – 12 months	***Before*** Chromium: 25-10,000 ***After*** Chromium: 75 - 90% removal	$50-150 per ton
Lynntech, Inc.	Low permeability soils (Clay)	N/A	N/A	N/A	N/A	N/A	Chromium, Lead	3 – 9 months	***Before*** N/A ***After*** Lead: ***65%*** removal	$65-125 per cubic yard
Electrokinetics, Inc. - CADEK™ Electrode system	Kaolinite	N/A	3 feet	N/A	Proprietary conditioning agents	30 feet by 60 feet Depth of 3 feet	Lead	6 – 8 months	***Before*** 1000 – 5000 ***After*** N/A	N/A

Table 2.3 Electokinetic pilot or field scale demonstrations (all values are in ppm) (Cont’d)

Developer	Soil Type(s)	Electrode Spacing	Electrode Depth	Voltage/ Current	Processing Fluid	Remediation Area	Contaminant Treated	Time Duration	% Removal Efficiencies	Cost
Geokinetics International, Inc., (Lageman, 1993)	Peat Soil	9.84 feet	Cathode 0.16 feet, Anode 3.28 feet	N/A	N/A	229 feet by 9.84 feet Depth of 0.06 – 0.16 feet	Lead, Copper	430 hrs	Pb: 300-5000 Cu: 500-1000 After Pb: 70 % & Cu: 80 % removal	N/A
Electrokinetics, Inc. (EK) - Electro - Klean™ Soil Processing	Saturated/ unsaturated sands, silts, fine-grained clay, sediments	3 feet	3 feet	450-600 volts 15 – 20 amperes	Acetic Acid	Lead contaminated site: 10 feet by 34 feet Depth of 3 feet	Uranium, Zinc, Thorium, Lead, Radium, Phenol, Arsenic,Copper, Cadmium, Chromium, Nickel, , BTEX compounds,	1 – 6 months	***Before*** Ur: 1000 pCi/g Th: 50-300pCi/g Rd: 1000 pCi/g Pb: 2000 ***After*** Ur : 95% & Pb : 25-50% removal	$50-150 per ton
Isotron Corporation-ELECTROS-ORB™ Process	Mixture of sand and kaolinite	N/A	N/A	N/A	N/A	N/A	Uranium, Mercury	N/A	***Before*** Mercury: 10 –20 ***After*** N/A	N/A
Geokinetics International, Inc., (Lageman, 1993)	Sandy clay	4.92 feet	N/A	0.8 volt/cm	N/A	49.2 feet by 19.68 feet depth of 1.31 feet	Zinc	1344 hours	***Before*** Zinc: 70-5120 ***After*** Zinc: 30-4470	N/A
Gent et al. (2004)	N/A	Anode-Cathode: 15 feet	Upto 9.84 feet	40 – 60 volts	Citric Acid	N/A	Chromium	180 days	***Before*** Cr: 180-1100 ***After*** Cr: 78% of soil volume cleared to background levels	200kwh per m^3

Table 2.4 Synthesis of field data report for removal of chemicals by electrokinetics (after Acar and Hamed 1991)

No.	Researcher Soil/Contaminant	Current density (mA/cm^2)/ Voltage [V/cm]	Duration (h)	Area (m x m)	Energy (kWh/m^3)	Remarks
1	Puri and Anand (1936) High pH soil - NaOH	1.35 [2.44]	6	4.5 x 4.5 depth - 1.05	N/A	Anode: 0.9m x 1.8 m, Cathode: perforated iron pipe 0.1m dia, 1.8 m long
2	Case and Sutshall (1979) Alluvial deposites – Sr^{90}	0.3 [0.05]	5.4	11 x 5	N/A	Electrodes: 1.7 m SS rods, 25 anodes on the arc and 1 cathode at the centre
3	Segall, et al (1980) Dredge material (Cd, Zn, Pb, As, Fe)	[0.01 – 1.0]	N/A	N/A	N/A	Distance between electrodes 3 – 5 m
4	Lageman (1989) Sandy Clay - Zn	0.8 [0.4 – 0.2]	1344	15 x 6 depth - 0.4	287	2 cathodes at 0.5m depth 33 anodes at 1 m depth, cathode – cathode distance and anode to anode distance 1. 5 m
5	Lageman (1989) Heavy Clay - As	0.4 [0.4- 0.2]	1200	10 x 10 depth 2	270	Cathode in 2 rows; 1st row 0.5m & 2nd row 1.5m depth, 36 anodes in 3 rows at 2m depth, 2 rows of 14 and 1 row of 8, cathode – cathode distance: 3 m, anode – anode distance: 1.5m
6	Lageman (1989) Dredged Sediments - Pb	N/A	430	70 x 3 depth 0.5	N/A	Cathode was laid horizontally, anode: vertical, cathode – anode: 3 m, anode – anode: 2m
7	Banerjee, et. al. (1991) Silt/ Silty Clay - Cr	2 - 4	< 72	N/A	N/A	Nine field experiments were conducted in array of electrodes. Combine hydraulic and electrical potential were applied. Steel reinforcing bars for electrodes.

N/A = Not Available.

2.4 ELECTROKINETIC GROUTING

2.4.1 History of Electro-osmotic Treatment

The electro-osmosis was discovered by Reuss in 1809. It refers to the movement of a liquid phase through a stationary solid phase under an applied moderate electric field. Some 50 years ago Casagrande (1949, 1952) led the way by using electro-osmotic technique to stabilize the soft soils underneath Canadian railway areas followed by Gray & Mitchell (1967), Esrig et al. (1968), Mitchell & Wan (1977) and Lockhart et al. (1963). They also evidenced the consolidation of soft clays by electro-osmotic treatment at laboratory level which has generated much interest in geotechnical engineering. Dearstyne & Newman (1963), De Beer et al. (1966), Hansbo et al. (1970), Caron et al. (1968) and Eggestad & Foyn (1983) followed the same phenomenon in field experimentation. Casagrande (1952,1983), Perry (1963) and Wade (1976) reported several successful case records where, electro-osmotic treatment has been used to control pore water, generally at excavation sites. Milligan (1995) used this process to improve friction pile capacity.

2.4.2 Ground Improvement with Electro-osmosis

Improvement of the engineering properties of adverse ground conditions is known as Ground Improvement. Electro-osmotic treatment is one of the soil improvement techniques to improve the strength of soft soils. Lo & Ho (1991) attempted to find out the effectiveness of electro-osmosis in strengthening the soft sensitive (Leda) clay at the Gloucester test fill site. Kim et al. (1997) found that the electro-osmotic drain consolidation was highly affected by the concentration of electrolyte in soils and discovered that characteristics of electro-osmotic drain consolidation for marine clay in Korea met good agreement with Esrig's theory. Bergado et al. (2000) investigated using the small size electro-osmotic cell and the large consolidometer on the response of reconstituted soft Bangkok clay. Test results indicated that employing electro-osmosis to induce consolidation produced a 3 to 4·4 times faster rate of consolidation and observed 11.6 - 58.0 % increase in shear strength with the reduction of water content for treated samples. In contrast, only 9.8-19.5% increase in shear strength was achieved without treatment. It was found that the 120 V/m voltage gradients and the 24h duration of polarity reversal interval had maximum effect on the shear strength distributions and settlements between the electrodes. Ei Naggar & Routledge (2004) used the electro-osmotic treatment to increase the axial and lateral capacity of piles installed in soft sensitive clay at laboratory scale and the results obtained from the axial load tests showed that the treatment had increased the capacity of the piles up to 45%. Direct electric current has been applied to the soils to improve the stability of excavations, slopes, and embankments; to increase the capacity of piles; and to increase the strength of clays.

2.4.3 Chemical grouting with electro-osmosis

To enhance the effect of electro-osmotic improvement, the procedure of injection of chemical solution into soil during electro-osmotic treatment has been developed. Under the influence of electric field physical and chemical properties of soil will be altered because of the reaction between soil particles and chemical solutions that we inject ion exchange, water adsorption and so forth. Srinivasaraghavan & Rajasekaran (1994) attempted to investigate the beneficial changes in the engineering properties of marine clay using electro-osmotic grouting with three inorganic additives such as NaCl, KCl and $CaCl_2$. Ozkan et al. (1999) investigated the injection of representative species into kaolinite to achieve stabilization by homogeneous precipitation of the species, pore fluid reconstitution and appropriate ion exchange mechanism by simultaneous injection of cations at the anode compartment and anions at the cathode compartment under electric field, where the co-ions were appropriately selected to control and manipulate the electrolysis reactions as a means to meet the specific stabilization objectives. Chen & Murdoch (1999) derived a unique configuration of horizontal sheet-like electrodes which was used in the field at a site in Ohio and underlain by silty clay glacial drift to induce electro-osmotic flow and to characterize the effects of electro-osmosis on soil properties (e.g., electrical conductivity and pH). Alshawabkeh & Sheahan (2003) described about electro-grouting, to mechanically stabilize soils with low hydraulic conductivity (k) using ion migration induced by applied electric fields. The advantage of the new method is that it can increase soil shear strength with little or no associated volume change. In contrast to induced consolidation, electro-grouting does not rely on pore fluid movement but rather on the migration of charged grouting agent ions to improve strength and reduce water content. Electro-grouting could be an effective in-situ ground improvement tool in soft soils, particularly where ground movements need to be minimized. Barker et al. (2003) described the application of electro-kinetic stabilization to clay soils. Electro-kinetic stabilization combines the processes of electro-osmosis and chemical grouting, and it is most effective in silty and clayey soils where the hydraulic conductivity is low. Barker et al. (2003) introduced Sodium silicate ($NaSiO_2$) and calcium chloride ($CaCl_2$) solutions at the cathode and the anode respectively. The results indicated significant increase in the pore water pressure close to the anode and reduction of pH along the test section was observed. Balasubramaniam et al. (2003) examined suitable soil improvement techniques, especially with chemical additives. The strength and compressibility characteristics of treated and untreated samples of soft clay are studied with the oedometer tests, unconfined compression tests, and tri-axial tests. The treated samples showed very small pore-pressure development in the undrained tests and similarly, small volumetric strains in the drained tests. Mohamedelhassan & Shang (2003) explained that the effectiveness of electro-osmotic treatment in transporting water can be predicted qualitatively or semi-quantitatively from the zeta potential of the soil solid suspension. The influence of pore fluid pH on the zeta potential of the soil was also investigated. The study provided important information for the use of electro-kinetics to assist in situ artificial cementation of calcareous soils for offshore foundation applications. Asavadorndeja & Glawe (2004) presented a scheme for enhancing the efficiency of electro-kinetic stabilization to obtain more uniform improvement. They developed a depolarization technique in which hydroxide ions depolarize hydrogen ions generated from electrolysis is applied at the anode. This technique prevents the formation and migration of the hydrogen ions (which hinder the stabilizing processes) into the soils. The injected calcium ions and hydroxide ions react with the dissolved silicates and aluminates in the clay to form cementing agents—calcium silicates and/or aluminum hydrates. They also measured the increases in strength of up to 170% immediately after treatment and up to 570% after a 7 days curing. These results demonstrated that this sample technique could significantly improve the quality of electro-kinetic stabilization in soft soils. Burnotte & Lefebvre (2004) described the results about a field setup during the 48 days of the electro-osmotic treatment and results of the post-treatment geotechnical investigation after 12% of clay compression due to electro-osmotic consolidation. These results confirm that soft clay deposits can be successfully treated by electro-osmotic consolidation, at a competitive cost compared with other alternatives, when power losses at the soil-electrode contact are controlled. Paczkowska (2005) presented the results of research on highly swelling and contractible Pliocene clays. The introduction of the polymer poly (methyl methacrylate) (with pendant chains possessing organic cations (poly-DEAH$^+$Cl$^-$)) into the clay and the dewatering of the clay were performed using the electro-osmosis technique.

2.4.4 The mechanism of electro-osmotic chemical treatment

Electro-osmosis is the movement of water and whatever is contained in water through a porous media by applying a direct current (DC) field. For purpose of research, the porous media can be different soils and distribution kinetics of calcium is to be evaluated under the influence of constant voltage, concentration of calcium chloride and time intervals.

2.4.4.1 Double layer theory

Although double layers is a general interfacial phenomenon, the first thing needs to consider is electrode-electrolyte interfaces, because of their importance in electrodekinetics and because the theory leads on to a general treatment of all phenomena. Double layer is a structure that appears on the surface of an object when it is placed into a liquid. This object might be a solid particle, or gas bubble, or liquid droplet, or porous body. This structure consists of two parallel layers of ions. Double layer is fundamental to the electrochemical behaviour of electrodes. The schematic diagram of double layer is shown from Fig. 2.13 to 2.17. The earliest model of the electrical double layer was usually attributed in 1853 by Helmholtz. Helmholtz treated the double layer mathematically as a simple capacitor, based on a physical model in which a single layer of ions is adsorbed at the surface. Later in 1909 by Gouy, and in 1913 by Chapman made significant improvements by introducing a diffuse model of the electrical double layer, in which the electric potential decreases exponentially away from the surface to the fluid bulk. Gouy-Chapman model fails for highly charged double layer. In order to resolve this problem, Stern (1924) suggested introduction of additional internal layer, which is now called the Stern layer **(Fig. 2.18)**. Combined Gouy-Chapman-Stern model is most commonly used now.

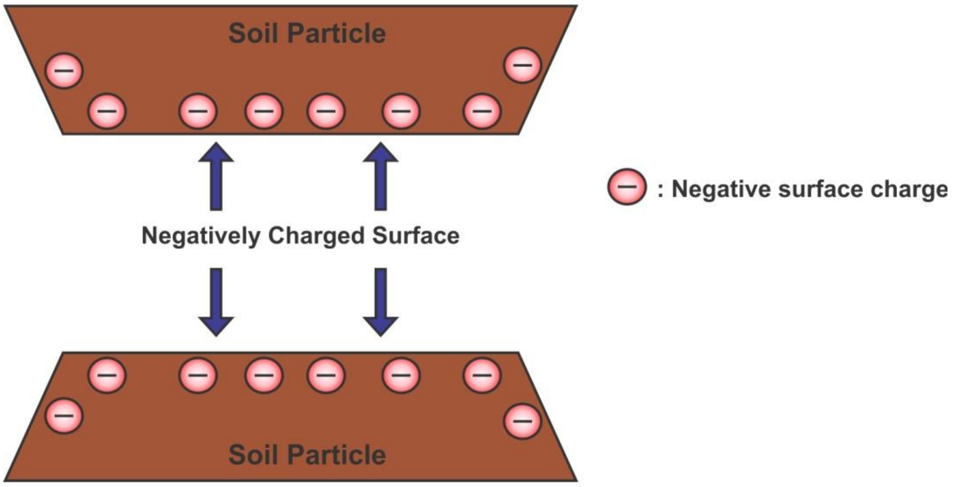


Fig. 2.13 Clay Particles Carry Negative Charge (Chien, S.C. (2003))

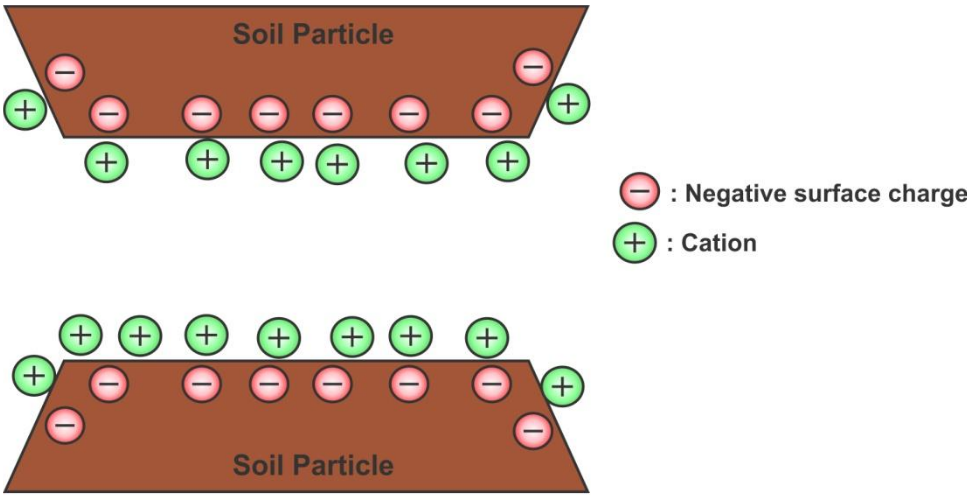


Fig. 2.14 Negative surface charge attract positive charge (Chien, S.C. (2003))

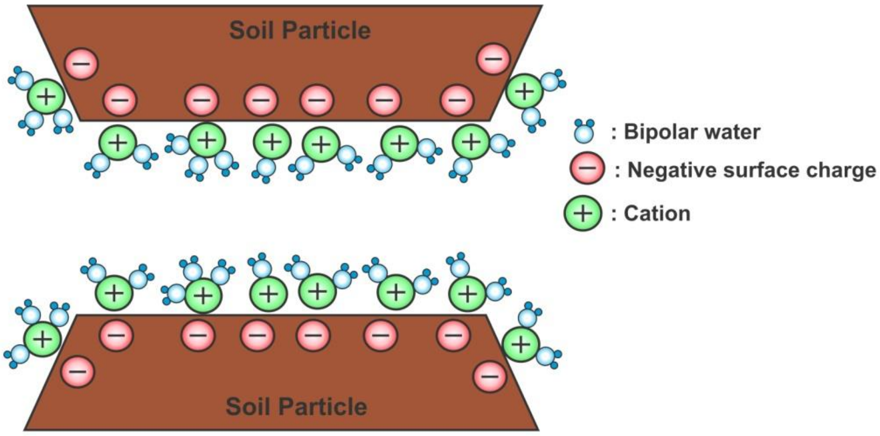


Fig. 2.15 Cations attract bipolar water molecules to form hydratized cations (Chien, S.C. (2003))

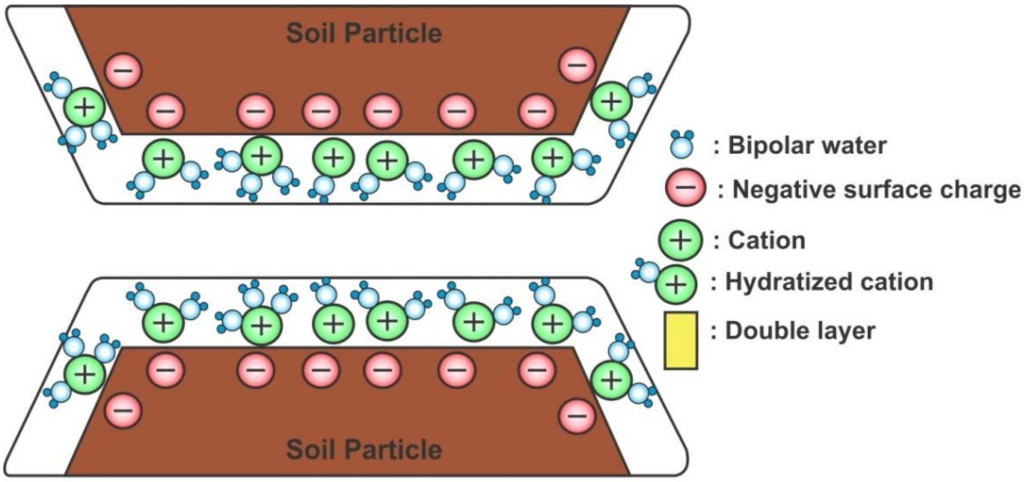


Fig. 2.16 Hydratized cations form “Double Layer” along pore wall (Chien, S.C. (2003))

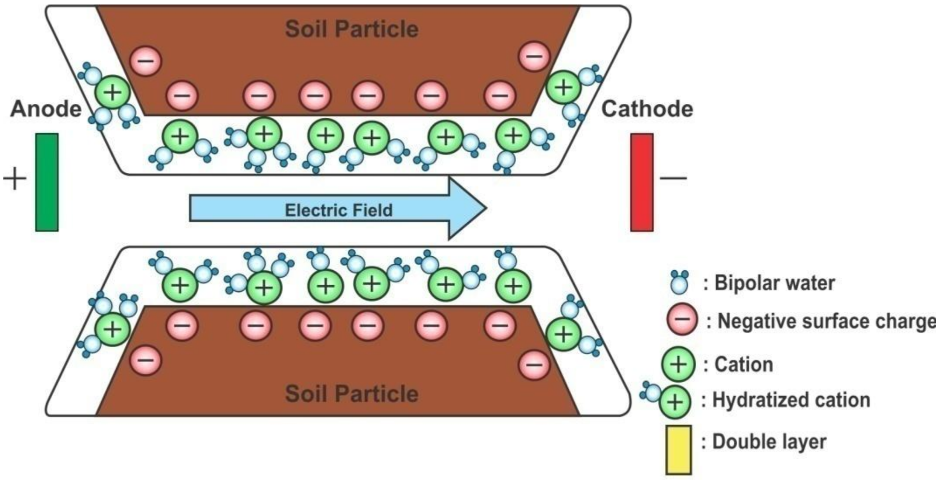


Fig. 2.17 Anode has positive charge; cathode has negative charge (Chien, S.C. (2003))

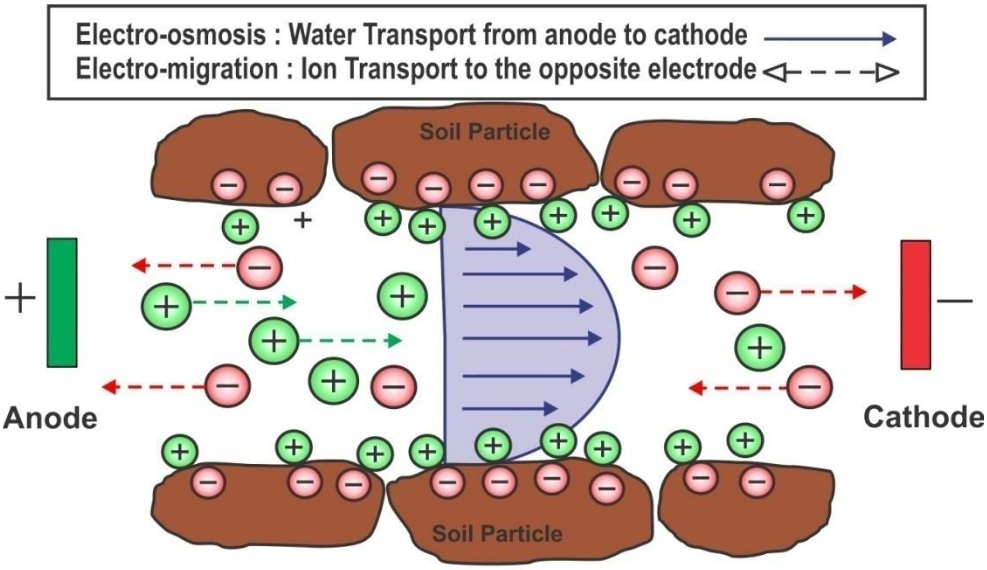


Fig. 2.18 Principle for Electrokinetic Grouting (Chien, S.C. (2003))

2.4.4.2 Chemical Reaction of Electro-osmosis

During the electro-osmosis trial, the process will produce several chemical reactions. These chemical reactions are hydrolysis, oxidation and reduction of electrode and cation exchange reaction.

- **Hydrolysis:** Hydrolysis is a chemical reaction or process in which a chemical compound is broken down by reaction with water. It is the type of reaction that is used to break down certain polymers, especially those made by step-growth polymerization. Such polymer degradation is usually catalyzed by either acid or alkali, attack often increasing with strength or pH. In this case, i.e., electro-osmotic treatment, hydrolysis can also refer to the electrolysis of water. In hydrolysis, application of direct current through electrodes immersed in water results in oxidation at the anode and reduction at the cathode (Acar and Alshawabkeh 1993). These fronts will migrate towards each other as hydrogen and hydroxide ions move under the electrical gradient, with the soil being neutral where two fronts meet. Previous research has found that the acid front moves over a much greater distance than the base front (Acar et al., 1990).

- **Oxidation Reduction of Electrode:** The reactions that occur between the electrodes and the pore water depend on the characteristics of the pore water and the material properties of the electrodes. From corrosion theory it is known that oxidation occurs at the anode owing to the loss of electrons, while reduction occurs at the cathode (Owen and Knowles, 1994).

  Oxidation at the anode: $M \rightarrow M^{2+} + 2e^-$

  Reduction at the cathode: $O + 2H_2O + 4e^- \rightarrow 4(OH)^-$

  Combined: $M^{2+} + 2(OH)^- \rightarrow M(OH)_2$, where M is the material of the electrodes.

2.4.5 Factors Affecting the Electrokinetic Grouting Process

Various factors which affect the process of electrokinetic grouting are soil composition, periodic supply, ionic radius, pH, nature and arrangement of electrode, soil chemistry, soil structure.

- **Effect of Soil Composition:** One of the factors affecting the process of electrokinetic grouting is soil composition, since different soils have varying sizes of soil particle distribution which affects the process in terms of efficiency. EKG process is most suitable in silty soils but it is ineffective in gravely soils. It is effective in liquefiable soils upto a certain extent.

- **Effect of Periodic Supply:** Research has shown that the applied electric potential produces complex physical, chemical and electrochemical changes within clay soils that affect mass transfer and overall efficiency. To study the effect of pulsating supply, Richard E. Saichek et. al. (2004) conducted various experiments to determine the contaminant mass removal by a periodic voltage application. The voltage gradient was applied continuously or periodically, under relatively low voltage (1.0 VDC/cm) and high anode buffering (0.1M NaOH) as well as high voltage (2.0 VDC/cm) and low anode buffering (0.01M NaOH) conditions. The periodic voltage application generates an electric current that follows an up and down pattern. The current decreases rapidly during the time interval when the voltage is continuously applied, but during the down time when the voltage is not applied, additional ions become solubilized or the diffuse double layer becomes less polarized, so when the voltage is reapplied the current is significantly higher than it was before the down time started.

- **Effect of Ionic Radius:** Ions of one type can be replaced with ions of another type. The ease with which an ion can replace an ion of another type depends on the valence, the concentration of the ions, and its ionic size. The mobility of an ion under the influence of an electric field in soil depends on a number of factors such as porosity, permeability of the medium, applied current density or voltage gradient, charge and size of ionic species.

- **Effect of pH:** Soil pH is an indication of the acidity or alkalinity of soil and is measured in pH units. Soil pH is defined as the negative logarithm of the hydrogen ion concentration. The electrolysis reaction affects the EKG process because the ionic products may electromigrate and/or they may be transported by electroosmotic advection towards the oppositely charged electrode location. An acidic front of solution may move from anode towards the cathode, and/or alkaline front of solution may move from cathode towards the anode. The rate of electromigration could be affected by ionic mobility, and since hydrogen ions are smaller and have 1.76 times the ionic mobility of hydroxyl ions, the acidic front generally moves faster through the soil. In addition, rate of electrolysis reactions at electrodes could affect the generation and migration of the hydrogen and/or hydroxyl ions. For low acid buffering clayey soils, such as kaolin, the inflow of H+ ions has the effect of causing the charge on the mineral surface to be more positive, which decreases the electroosmotic flow towards the cathode. Shapiro and Probstein (1993) found that adding a pH control solution to the anode reservoir helps to counteract or neutralize the electrolysis reaction at the anode, and the result is a higher and more sustained electroosmotic flow.

- **Effect of Electrode Spacing:** The number of electrodes required for 1-D application (Fig 2.19) depends on spacing between electrodes of the same polarity (e.g., anode-anode or cathode- cathode spacing). Decreasing the spacing between same polarity electrodes minimizes the area of inactive electric field, but increases the cost of the process. The same situation applies for 2-D configurations (Fig 2.20). In general, the goal of 2-D application is to achieve axi-symmetrical (or radial) flow towards a centre electrode. Outer electrodes (anodes) are placed at specific distances from the centre cathode to achieve relatively radial flow. The electrodes can be placed in a hexagonal or square configuration. Hexagonal (honeycomb) electrode configuration consists of cells; each contains a cathode surrounded by six anodes. The square configuration consists of a cathode and four anodes surrounding cathode. Hexagonal and square grids generate 2-D, nonlinear electric fields. Areas of inactive electric fields will develop depending on the configuration selected. Because this impacts the cost of electrodes, it will be necessary to select the configuration with optimum number of electrodes per unit area of the ineffective electric field. To study the optimization of 2-D electrode configuration for electrokinetic remediation, Akram et. al. provided a preliminary design approach using simplified assumptions for 1-D and 2-D in situ implementation of electrokinetic soil remediation. A practical approach is provided for evaluating electrode requirements and development of ineffective electric field spots for different 1-D and 2-D electrode configuration. Formulation is provided for calculating cost components of the process, including electrode, energy, chemicals, post treatment, fixed and variable costs.

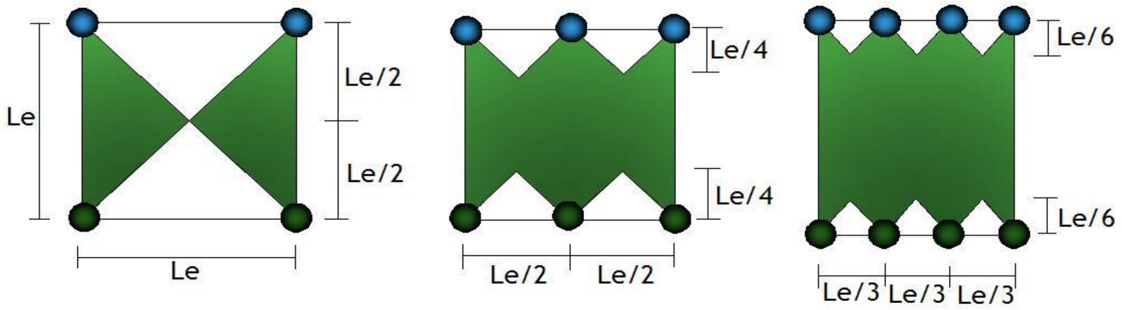


Fig. 2.19 1-D Configuration of Electrodes

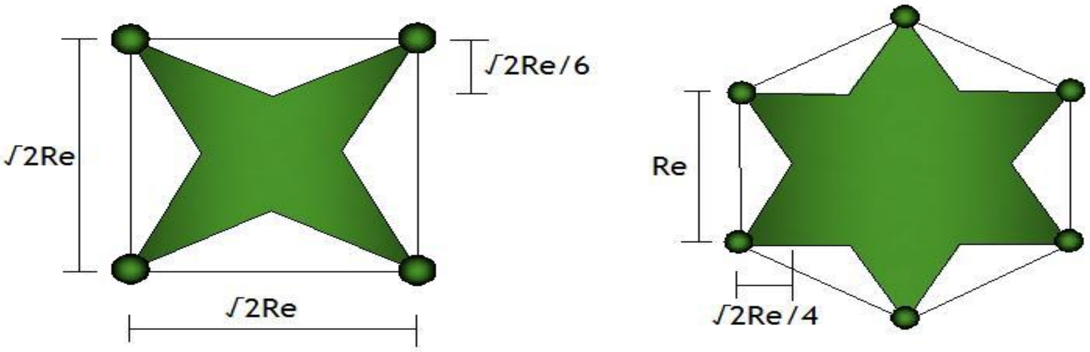


Fig. 2.20 2-D Configuration of Electrodes (Virkutyle et al., 2002)

- **Soil Chemistry:** Some attempts have been made to examine the various effects of soil chemistry on electro grouting; for example, the importance of organic matter, ion oxides (Reddy et. al., 1997) or both (Ribeiro and Mexia, 1997). Characteristics of the soil, which influence kinetics of contaminant removal, include adsorption, ion exchange, and buffering capacity (Grim, 1968; Sposito, 1984).

- **Soil Structure:** During electro remediation (Mitchell, 1991; Yeung, 1994) other alterations may occur to soil structure and properties. Certain clay minerals, such as montmorillonite, show dramatic changes, both physical and chemical, resulting in water loss and shrinkage (Grundl and Reese, 1997). Clogging of pores and eventual cessation of flow can result from deposition in the soil of compounds such as metal hydroxides which may be formed by reaction between hydroxyl ions near the cathode and heavy metal contaminants. For remediation of metal contaminated soils, it is necessary to prevent precipitation in the soil of insoluble metal compounds.

2.5 ELECTROKINETIC GEOSYNTHETICS

New applications for geosynthetics have been identified if they can provide an active role, initiating biological, chemical or physical change to the matrix in which it is installed as well as providing the established functions. This can be achieved by combining the electrokinetic phenomena of electroosmosis, electrophoresis and associated electrokinetic functions such as electrolysis with the traditional functions of geosynthetics of drainage, filtration, containment and reinforcement to form electrokinetic geosynthetics. Electrokinetic geosynthetics (eKG) have been identified as a platform technology, which combines a wide variety of materials, functions and processes to perform such diverse functions as dewatering, strengthening and conditioning in materials such as soils, sludges, slurries, tailings and composts. Applications have been identified in a range of industrial sectors including water, mining, civil and environmental engineering, food and sport. The benefits and drivers for the use of eKG applications include, countering climate change, reduction in carbon footprint of processes, reduced costs, water recovery and compliance with legal directives. Environmental legislation is driving organisations to ensure that their operations are continually improving on energy efficiency and environmental protection. In the mining industry the use of electrokinetic dewatering of tailings produces water recovery and a major reduction in the carbon foot print of mining operations, both of which are growing priorities. On a technical level the use of electrokinetic techniques can be used to counteract climate change and reduce the risk of liquefaction of tailings. In terms of waste reduction and efficiency, full scale field trials have shown that the invention of eKG has meant very efficient utilisation of electrokinetic functions. In the biological dimension the effectiveness of eKG methods relates to increased biological activity in relation to increased oxygen availability and warmer temperatures.

Electrokinetic geosynthetics (eKG) have been identified as a platform technology, which combines a wide variety of materials, functions and processes to perform such diverse functions as dewatering, strengthening and conditioning in materials such as soils, sludges, slurries, tailings and composts. Applications have been identified in a range of industrial sectors including water, mining, civil and environmental engineering, food and sport. Table 2.5 shows the main technical components which form the backbone of eKG technology, giving out fourteen separate functions between them. By combining the different functions a range of eKG materials can be produced each with unique properties which may be selected and controlled according to materials and settings in which the eKG is used, physical and chemical design of the eKGs, electrical control and operation of the eKGs, management of the boundary conditions at the eKGs. A wide range of new applications have been established for eKG materials which cannot be addressed by conventional geosynthetic materials.

Table 2.5 Functions used in practical applications of eKG

Method	Function	Effects
Electrokinetic EK	Electroosmosis	Water Flow, Pore pressure change Volume Change
	Electrophoresis	Particle movement, Particle orientation
	Iron Migration	Solute Movement
	Electrolysis	Oxygen evolution, Hydrogen evolution, pH changes
	Heating	Joule heating (electrode), Resistive heating (soil)
	Oxidation	Soil cementation, Reduction in soil plasticity
	Reduction	Electro-winning of metal ions, Evolution of ammonia
Geosynthetic G	Drainage	Water flow, Gas flow
	Reinforcement	Tensile strength, In-plane stiffness
	Filtration	Barrier to solids entrained in flow
	Separation	Strengthening & prevent mixing
	Containment	Physical containment of solids
	Membrane action	Barrier to flow(containment of fluids)
	Sorption	Capture of liquids or dissolved species

2.5.1 Drivers for Development and Use of EKG Materials

In the mining industry the use of electrokinetic dewatering of tailings produces water recovery and a major reduction in the carbon foot print of mining operations, both of which are growing priorities. On a technical level the use of electrokinetic techniques can be used to counteract climate change and reduce the risk of liquefaction of tailings. In terms of waste reduction and efficiency, full scale field trials have shown that the invention of EKG has meant very efficient utilisation of electrokinetic functions. The performance of EKG systems results in reduced costs. The electrokinetic belt filter press exceeds the performance of dewatering centrifuges but uses only 1/3 the power for an equivalent throughput. Similarly in sports turf applications the use of EKG to improve plant tolerance to shaded conditions would require an electrical running cost of less than $1/10^{th}$ of an artificial lighting system. Improved speed generally relates to faster water flow and associated mechanical or volumetric changes associated with electro osmotic flow. In the biological dimension it relates to increased biological activity in relation to increased oxygen availability and warmer temperatures. Improved performance relates to the ability of EKGs to be active agents in whatever setting they are in. The use of ePVDs to consolidate soft ground can speed up the period of consolidation from 2 years to less than six months.

2.5.2 Factors affecting Electroosmotic Flow

- **Porosity:** The greater the proportion of the material that is composed of voids filled with water then the greater the opportunity for flow. So, whilst K_e is independent of grain size (and by association a range of pore-throat diameters) it is not independent of porosity, i.e. the overall proportion of the material that is void. Therefore in dewatering applications, K_e is likely to gradually reduce as the material compacts. This will be observed as a reduction in flow and can be calculated according to volume changes measured.

- **Zeta potential**

Zeta potential is probably the most variable parameter defining Ke (with porosity a close second). Zeta potential is not a fundamental property of the material and varies according to the salinity of the pore fluid and the pH. Zeta potentials of clays and sludges are usually negative and represent the potential in mV at the junction between the mobile and immobile parts of the boundary layer. Thus a very low (or high negative value) is preferable. Increasing salinity tends to reduce the negativity of the zeta potential by compressing the boundary layer. A high pH has the effect of increasing the negativity of the zeta potential.

- **Permittivity:** The permittivity of the water defines the attenuation of an electric field and will be reduced by increasing the electrical conductivity of the water. This means that increasing pore water salinity has multiple detrimental effects on Ke.

- **Viscosity:** Viscosity is related to temperature and dissolved solids but the range is likely to be small except where long chain organics are involved. Excessive dosing of material to dewater with polymer flocculants may have an effect of reducing Ke and thus electro osmotic flow.

- **Mineralogy/ Pore Water Interaction:** In the absence of data on K_e or zeta potential it is necessary to make reference to other factors which will help to elucidate the potential for electro osmotic flow. Electro osmotic flow will occur best in those situations where electro-negativity of the zeta potential is of greatest magnitude, double layer is of greatest thickness (i.e. mobile portion of the boundary layer is maximized) and electro osmotic efficiency (defined as the volume of water moved per unit charge) is maximised.

2.5.3 Electro-osmotic Efficiency

Electro osmotic efficiency is defined as the quantity of water moved per unit of electricity and is proportional to K_e (and its contributing factors) and inversely proportional to conductivity σ (and its contributing factors). The factors of the mineralogy which have a positive affect on the potential for good electro osmotic include: high water content w_c; clay minerals with low cation exchange capacity (CEC), low valency exchange cations, high surface charge density and a high surface area, a water composition which has low conductivity (σ), low salinity, a high pH and a low surface charge density per unit pore volume A_0. The effects are shown schematically in Figures 2.21 and 2.22. In the absence of knowledge about the clay mineralogy, a particle size distribution curve can be used to estimate the proportion of clay that may be present. It should also be noted that the absence of clay does not necessarily indicate the lack of potential for electro osmotic flow. The key factors are the origin and magnitude of the negative surface charges and the salinity of the pore water which would act to compress the double layer and thus minimise the effectiveness of the surface charge.

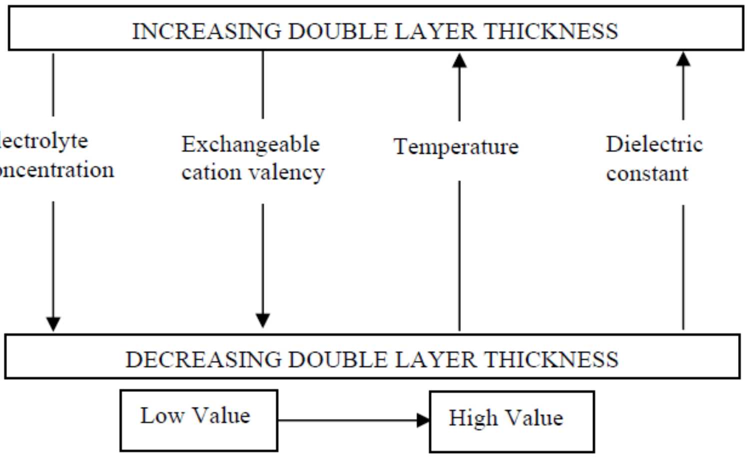


Fig. 2.21 Factors affecting the thickness of the double layer (Pugh 2002)

2.5.4 Cost of Treatment

Cost can be the single driver for the use of EK technology. However, the use of electrokinetic methods may involve alternative treatment strategies and the overall cost can be dominated by external requirements such as the cost of transport or disposal costs. Examples of the latter are provided by electrokinetic dewatering of sewage and mine tailings, (McLaughlin 2005, Huntley et al 2006).

2.5.5. eKG Material Developments

The current forms of eKG materials which have been or are under development are illustrated in Table 2.7, based on the electrokinetic functions of electro osmosis, joule heating and ion migration, together with the geosynthetics functions of drainage, filtration and reinforcement. It is also clear from the table that there is ample scope for new products and applications by developing combinations which include the geosynthetic functions of separation, containment, membrane action and sorption. Some of these potential applications relate to environmental cleanup.

2.5.5.1 Physical form

Geosynthetics can be made singly or from combinations of woven, non-woven, needle punched knitted, extruded or laminated materials and can be formed in any 2D or 3D shape. Electrokinetic geosynthetics are formed by the inclusion of conducting elements using woven, knitting, needle punching and extrusion or laminating techniques and can take the form of a conventional geosynthetic material. All geosynthetic materials have to fulfill the function for which they are designed and this is also the case with eKGs. However, some eKGs have a dual function having an initial *active* role which may be of short duration and which is followed by a long term *passive* role.

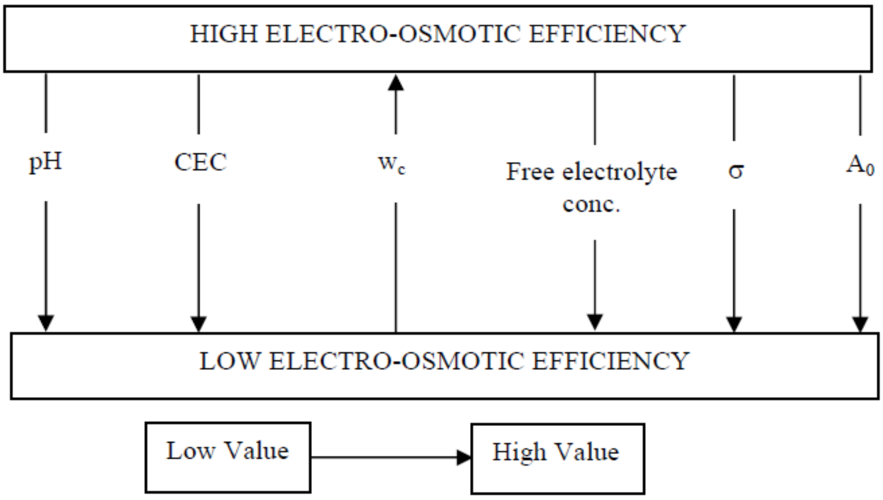


Fig. 2.22 Influence of soil variables on E-O efficiency (Pugh 2002)

2.5.5.2 Electrical design

The aim of the design of the electrical component of any eKG is to:

- Distribute current throughout the length of the electrodes whilst maintaining a sufficiently high voltage throughout the length or area of the eKG thereby minimising voltage drop.
- Maximise the effective area of contact of the conductive surface to the soil/sludge or material being treated.
- Optimise the total amount of conductive materials in the eKG without compromising the voltage or the contact area, whilst ensuring economic viability.
- Allow polarity reversal if required

- **Voltage drop:** Depending on the chemistry of the material being treated it is expected that the voltage will be limited to an operating voltage of approximately 40V. If the material has a high level of dissolved sulphate the permissible operating voltage can be raised to 80V if suitable materials are used to form the EKG. It is desirable to have a steep and stable voltage gradient and to limit voltage drop to 20% to ensure that the voltage is used, not to overcome resistance in the system, but to create electro osmotic flow. Voltage drop is minimised by reducing the current and or the resistance. However, it is inappropriate to reduce the current as it is this which drives electro osmosis, and attention is focused on the resistance of the conductive elements. Resistance is minimised by minimising resistivity, maximising the cross sectional area of the conductive elements and minimising the path length.

- **Maximising area of contact of the electrodes:** Current can only pass into the target material where it comes into contact with the electrodes, for effective treatment the area of contact must be maximised. This is achieved by:
    - Maximising the number of conductive elements
    - Maximising the circumference/cross sectional area ratio of conductive elements
    - Maximising the exposed area of the conductive element
    - Minimising the electrolytic production of gasses
    - Maximising the removal of electrolytically produced gasses.

- **Electrolytic gasses:** Hydrogen is released at the cathode and oxygen at the anode. The conditions at each electrode are different. The cathode is usually bathed in liquid for the duration of the treatment. Provided that the electrode functions so as to remove the hydrogen, there should be no net reduction in the proportion of surface area contact of the submerged or embedded cathode with the soil/sludge. The anode gradually becomes dried out due to electro osmosis. As a result the area of contact of the electrode may be reduced. This has a knock on effect such that, if the anode is not continually bathed in water, there is a greater possibility for menisci to be created and for gas drainage to be reduced. The aim of the anode therefore is to reduce the amount of gas produced and to vent the gas effectively. The former can be achieved by:
    - Reducing the current per anode (i.e. have more anodes than cathodes)
    - Include sacrificial elements that dissolve so as to transmit the current into the ground but without producing gas.

- **Polarity reversal:** Anodes and cathodes provide different functions and this can be reflected in their designs. However, in many cases a period of polarity reversal is desired, in which case it may be appropriate to use an anode as the cathode although this may incur a cost penalty.

2.5.5.3 Materials

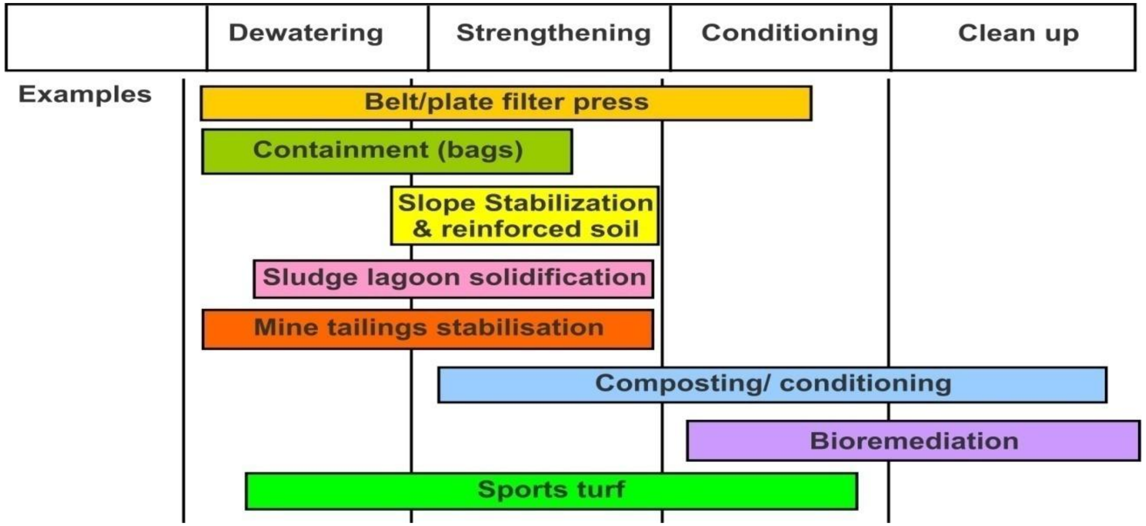
Depending on the design options chosen an EKG material will include several distinct components including: Corrosion resistant conducting elements, Corrodible conducting elements, Non-woven filter fabrics, Woven or knitted fabrics, Additional drainage media, Method for venting gases

- **Conductive elements:** Conducting elements can be formed from corrosion resistant material or by the use of mixed metal coatings (MMO) on suitable metals. Alternatively the conducting elements can be covered in electrically conducting polymer; however this may result in a large voltage drop.

Table 2.6 Embodiments of EKG technology that exploit specific electrokinetic and geosynthetic functions

EK	G Geosynthetic Functions				
	Drainage	Reinforcement	Filtration	Separation	Containment
Electroosmosis	ePVD, eMat, eStrip, Rekg, ePD, eFDC, eBFP, ePFP, eFCB	ReKG, eSN, eMat	ePVD, Rekg, ePD, eFDC, eBFP	eMat	eFCB
Electrophoresis	eBFP		ePVD		
Ion Migration	ePVD	eSN	ePVD, eBFP, ePFP		
Electrolysis of Water	eMat, eStrip			eMat	
Heating	EMat, eStrip		eMat	eMat	
Oxidation Reactions	ePVD	eSN			
Reducing Reactions	eBFP		eBFP		eFCB

Where: ePVD = Electrokinetic prefabricated vertical drain, eMat = electrokinetic mat, eStrip = electrokinetic prefabricated drain, ePD= Electrokinetic prefabricated drain – horizontal or sub horizontal, eFDC =electrokinetic filtration drainage curtain, ReKG = reinforcement EKG, eBFP=electrokinetic belt filter press, ePFP = Electrokinetic plate filter press, eFCB =Electrokinetic filtration containment bag, eSN = electrokinetic soil nail.



- **Corrodible conductive elements:** It can be beneficial to include sacrificial or corrodible elements into the structure of the eKG in order to:
    - Dissolve and thus pass current into the soil to reduce resistance at the electrode-soil contact (thus maintaining the voltage gradient which drives electroosmosis) without evolving oxygen. The advantage of dissolution as opposed to oxygen evolution is that dissolution avoids the loss of electrode – soil/sludge contact area associated with the formation of bubbles. Dissolution of metal also helps to 'soak-up' the high current demand at the start of treatment without resulting in the hydrolysis of water surrounding the anode. This means that the speed of desiccation of the anode is reduced such that a higher current density though the electrode will be maintained for a longer period as the treatment proceeds.
    - Release cations by dissolution of corrodible elements in order to contribute to the movement of water under the Helmholtz-Shmoluchowsky model of electro osmosis with the effect that K_e should increase. The choice of corrodible material and the amount to be included in the eKG will be determined by cost and the effectiveness in improving electro osmosis.
    - Release metal ions to combat liquefaction in silty/clay materials.

- **Cathodic applications:** During normal polarity operation, corrodible primary conducting elements (PAC) may be used as heavy duty current collectors. During reverse polarity, cathodes of normal polarity become the new anodes. In these situations corrodible materials will be consumed. Therefore, depending on the duration and frequency of reverse polarity operations, the new anodes must be either corrosion resistant or designed such that there is sufficient material present to last for the duration of the reverse polarity phase.

- **Venting gasses: I**n addition to imparting current into the ground, the removal of gasses is an essential physical functioning of some eKGs such as ePVDs. With increasing depth in the ground, lateral earth pressure improves physical contact between the soil and the ePVD, but at the same time makes it more difficult for gasses to be expelled.

2.5.6. Applications and Developments of eKG

In general terms the embodiments of EKGs currently being developed apply to six broad applications areas, Table 2.7A and B

2.5.6.1 Studies into Electrokinetic Function and Behaviour

Research carried out in Tsinghua University, China studied effect of electro-osmotic consolidation and salt concentration for kaolinite clay and change of various parameters during the process. It was observed that a higher salt content significantly increase the electric current in the soil mass, improving the power consumption and effluent flow, however the increase in effluent is not significant with salt content more that 0.01%. It can be concluded that the electro-osmosis treatment is not effective for the Kaolin clay with a high saline content.

Table 2.7A Industries, markets and sectors of current eKG applications and development

Industry	Market	Market Sector	eKG embodiment
Water	Sewage treatment	Dewatering machinery	EKG belt press, EKG plate press
		Composting	ePD system
		Dewatering	EKG filtration bags
	Water treatment	Dewatering	EKG plate press
		Consolidation	ePVD system
Food	Processed foods & drinks	Dewatering	EKG belt press & EKG bags
Mining	Copper	Stabilisation	ePVDs
	Diamond	Dewatering	EKG belt press
	Iron Ore	Dewatering	ePVDs
	China Clay	Product Dewatering	EKG plate press
	Coal & coal waste	Dewatering	EKG belt press & vaccum belt
	Tailing lagoon stabilization	Dewatering	ePVDs
	Combating liquefaction	Stabilization	ePVDs/& electrokinetic soil nails
Sport	Construction (Horticulture)	Football	ePD mat system
		Cricket	eMat twin mat system
		Golf	eMat & ePD system
	Maintenance	Football	eRibbon & ePD system

2.5.6.2 eK Reinforcement of Soft Clay Slopes

A series of model tests have been conducted in China to study the effect of EK reinforcement on increasing the stability of saturated soft clay slopes. The EK material used in the tests was formed from electrically conductive plastic with a resistivity of 0.064Ωm, (Zhuang et al 2006). Analysis of the results of the tests lead to the development of a new analytical theory for electrokinetic strengthening based on energy analysis. The new method has been found to be applicable for both saturated and unsaturated soil during the consolidation process if the soil is saturated at the beginning of the process, (Zhuang, 2005). A numerical simulation program for electro osmosis based on the energy analysis theory has been developed to simulate the model tests. Examples of the model test results and the results obtained by the numerical model are shown in Figures 2.23 and 2.24.

Table 2.7B Industries, markets and sectors of current eKG applications and development

Industry	Market	Market Sector	eKG embodiment
Civil Engineering	Ground Engineering	Dewatering	EKG filtration bags, EKG belt press
	Waterways engineering	Dewatering dredging	EKG filtration bags
		Embankment stabilization	ePVDs & electrokinetic soil nails
	Railway & highway maintenance	Slope & embankment stabilization	ePVDs & electrokinetic soil nails
	General and highway construction	Reinforced soil & consolidation	REKG, ePVD
	Brown field/ Land reclamation	Ground consolidation	ePVDs
	Highway maintenance	Waste solidification	EKG filtration drainage curtains
	Dewatering gully waste	Waste solidification	EKG filtration bags
	Nuclear waste	Waste solidification	EKG filteration bags
Geoenvironmental Engineering	Decontamination / Brown field development	Environmental	ePD system

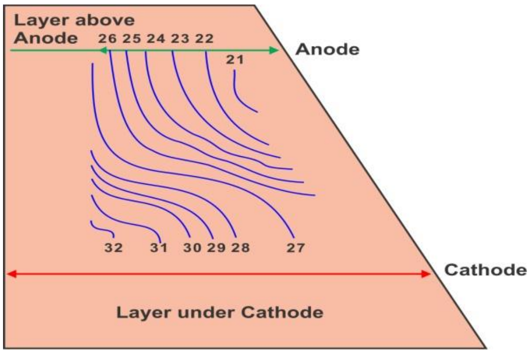


Fig. 2.23 Model test isolines of water content after electro osmosis (%)

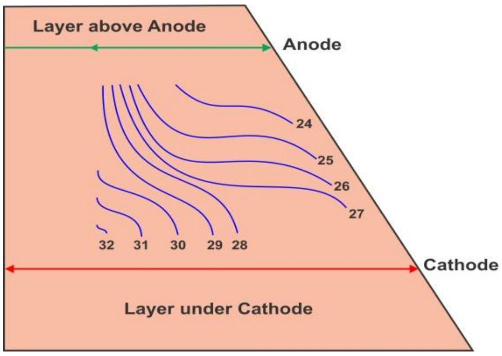


Fig. 2.24 Program simulated isolines of water content after electro osmosis (%)

2.5.6.3 Electro-osmosis to Consolidate and Strengthen Materials

Electrokinetic strengthening of soil has been undertaken by a number of practitioners including: Casagrande (1949, 1952, 1983), Fetzer (1967), Bjerrum et al (1967), Chappell and Burton (1975), Lo et al (1991a and b, 2000). The technique was also used for the dewatering and consolidation of mine tailings by; Sprute and Kelsh (1975), Lockhart (1983), Shang (1997). Cementation agents and bio remediation agents have been introduced into the soil through the technique by; (Mohomadel Hassan and Shang (2003), Shang et al (2004). In 1996, the concept of electrically conductive geosynthetics was introduced which offered the potential of an improvement in electrode performance, (Jones et al 1996). The first full scale EK drain was formed as an electrically conductive geonet core surrounded by a thermally bonded non woven filter fabric. The geosynthetic material used in the product was made conductive by the addition of carbon black powder to the conventional polymers alongwith monofilament wires located at the centre of alternate ribs to act as current distribution stringers (Nettleton et al 1998). The efficiency of the EK drain was studied by (Hamir et al 2001) who found it to compare well with copper electrodes. It is possible to make a conventional prefabricated vertical drain (PVD) conductive by the addition of conductive elements as illustrated by (Abiera et al 1999) who used a wrapping of carbon fibers. However, coating the PVD with conductive paste was unsuccessful.

2.5.6.4 Electro-osmotic Strengthening of Peat

The presence of soft peaty clays, sometimes in layers of thickness as high as 10m, is a major problem faced by engineers involved with new infrastructure developments, with no possibility of surcharge loading or use of deep mixing either due to technical or economical reasons. Electro-osmosis provides a potentially viable solution to this consolidation problem. Laboratory studies (Kulathilaka et al 2004) showed that the moisture contents of the peaty clays could be reduced effectively using a voltage gradient in the range of 25 – 120 V/m. The k_e/k_h ratio was greater than 0.1 m/V, and is in the acceptable range for treatment. The undrained shear strength, compression index, coefficient of volume compressibility and the coefficient of secondary consolidation were also improved. A notable finding of the electrokinetic tests on the peat was that conventional metallic electrodes were very susceptible to corrosion but that this problem was resolved by using eKG electrodes.

2.5.6.5 Dewatering of Mine Tailings and Wastes

Disposal of mine tailings, industrial wastes and wastes generated in water industry require use of impoundments which are amongst the largest manmade structures, with their stability being a major concern. The method of application of electrokinetic dewatering of wastes depends upon the nature of the material to be treated. Table 2.8 shows the potential eK methods available using different eKG material forms. The eK belt press is a continuous method of dewatering, electrokinetic prefabricated vertical drains (ePVDs) are used in-situ and eK bags and tubes are suitable for batch processes. The applicability of the different methods depends upon the volume and uniformity of the tailings or material to be treated and the rate of supply.

2.5.6.6 Dewatering of Diamond Mine Tailings

Metallurgical processing of kimberlite to obtain diamonds uses water as the processing and transport medium resulting in two broad types of discard material differentiated according to their dominant grain size: grits (>75 μm) and slimes (<75 μm). Water recovery prior to disposal offers advantages like reuse of water, reduction in size of the disposal facility, with an increased lifespan for a given facility, (Fourie, 2003; Welch, 2003). Paste and Thickened Tailings Disposal (P&TTD) processes reduce disposal volumes and recover water, the lack of it means that thickened tailings or pastes must be pumped in a liquid state to the disposal site using high pressure, high volume positive displacement pumps, Figure 2.25. Electrokinetic dewatering offers a method of further water recovery, reduction in energy costs and provides a means of reducing the carbon footprint of the mining process. Laboratory trials of electrokinetic dewatering for kimberlite tailings have established that they can be treated using electrokinetic belt press technology, Figure 2.26, (Lamont-Black et al 2007). Full scale trials at Kimberley have confirmed these results demonstrating major savings obtained with regard to energy costs associated with disposal, reduction in waste volumes requiring disposal, recovery of water and a significant reduction in the carbon footprint (CO_2) of the mining process. The dewatered tailings are suitable for transportation to the disposal site by conveyor, Figure 2.27.

2.5.6.7 eKG Stabilization of Slopes and Cuttings

Traditional methods for repair of slope failures include provision of additional drainage, replacing the fill with high quality material, slackening the slope by provision of dwarf walls at the toe or acquisition of additional land, although the latter is seldom possible. An ideal remedial method would be to effect a reduction in pore water pressures and an increase in shear strength of the material forming the embankment/impoundment using electro-osmosis thereby, reducing the risk of a slip plane developing. Electro osmosis can be used, either to aid construction of remedial works or as a means to effect permanent improvement (Fig. 2.28). In many slope materials there is a direct link between shear strength and water content and a small reduction in water content results in a significant increase in shear strength, which is used as the basic design criteria for the strengthening of clay railway embankments by Casagrande (1952) and the construction of steep/vertical structures formed from very weak materials, Glendinning et al., (2005) (Fig. 2.29).

Orientation of the electrodes depends on the nature of the potential slip. In the case of shallow slips and failure planes which do not pass beneath the toe of the embankment the ideal orientation of anodes/nails is slightly sub-horizontal, in which case the anodes are optimally orientated to act as nails, Davies (2007) (Fig. 2.30). Placing cathodes parallel to anodes can produce optimum electrical field conditions and simplifies installation; there are also benefits with regard to long term drainage when the cathodes have a sub horizontal orientation. In the case of a deep slip plane passing beneath the toe, orientation of the electrodes is determined by the geometry of the case.

Fig. 2.25 Disposal of Kimberlite slimes

Fig. 2.26 Electrokinetic belt press

Fig. 2.27 Dewatered tailing (11V, 78% DS) and recovered water

Table 2.8 Types of treatment and method

Materials	Treatment Method	Supply			
		Constant		Intermittent	
		Large Volume	Small Volume	Large Volume	Small Volume
Homogeneous	Existing EKG	Belt presses	Small belt	Temp. lagoon	Transport
		Plate presses	Transport		Mobile
		Centrifuges			dewatering
		EK Belt presses	EK belt	EKG Tubes	EKG Bags
Mixed	Existing EKG	Screen+ thicken & dewater	Screen thicken/ transport	Temp. lagoon	Screen thicken/ spread
		Screen + EK Belt / Tube	EKG Bags	EKG Tubes	EKG Bags

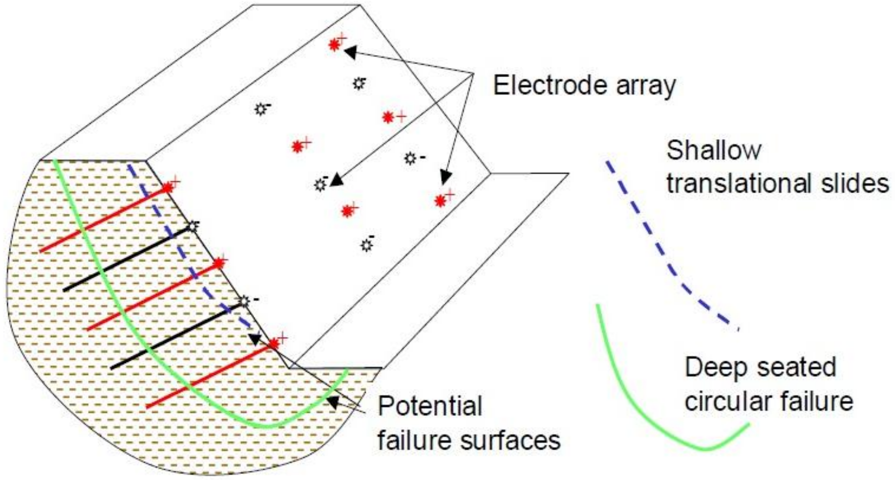


Fig. 2.28. Electrokinetic strengthening of slopes

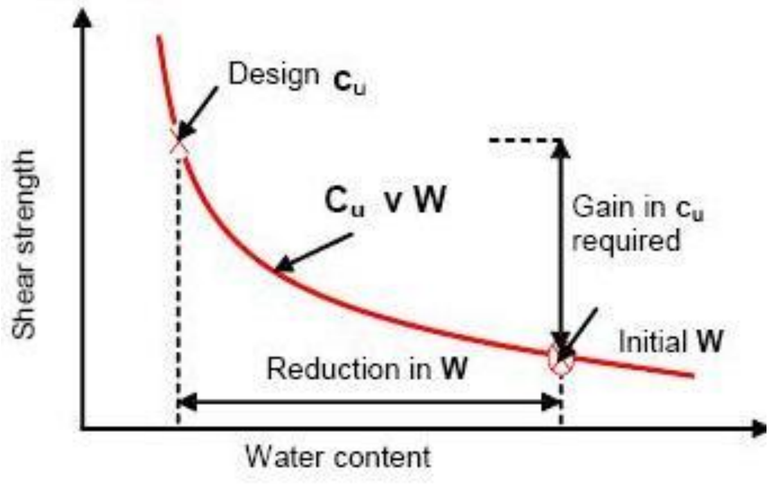


Fig. 2.29 Relationship between shear strength and water content

2.5.6.8 Reduction of Liquefaction Potential

Liquefaction of soil is a major geotechnical hazard which is very difficult to resolve, with situation of tailings being of particular concern since they can lead to major environmental damage. Many tailings dams are formed using thickened tailings which can be susceptible to liquefaction when subjected to a seismic event. Figure 2.31 shows the nature of thickened tailings which form part of the wall of a large tailings dam. The tailings are benign at low water content but are susceptible to liquefaction when saturated. Sections of the susceptible material are saturated and the dam is located in a seismically active zone.

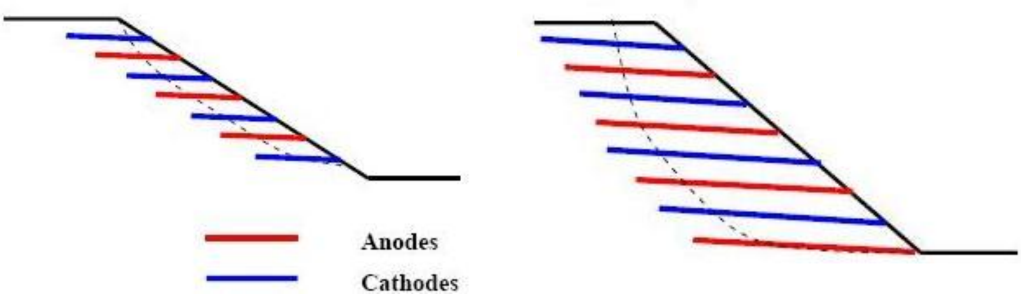


Fig. 2.30 Orientation of electrodes/nails/drains: option for a shallow translational slide (left), option for a deeper failure (right)

The behaviour of this material if stabilization using conventional soil nails is attempted is illustrated in a nail pullout test, Figure 2.32. This shows that the material round the nail liquefies completely on pullout nullifying any potential benefit of the nail, i.e. trying to stabilize the tailings dam by conventional soil nailing would be ineffective. However, if electrokinetic soil nails are used and the susceptible material is subjected to an initial period of electrokinetic treatment then the situation is changed and the thickened tailings no longer liquefies when the nail is pulled out, Figure 2.33. In this case there was a six fold increased in pullout resistance. The explanation is chemical cementation developed in the vicinity of the nail resulting from migration of metallic ions from the anode/nail. Ions precipitated from solution cement the silt around the anode thus stiffening the material and forming a ‘mini pile’; effects such as these have been reported by Milligan, (1994). Create a very strong bond with the anode/nail by the formation of a larger effective surface area for the nail thus increasing its pullout capacity. This is illustrated in Figures 2.34, and 2.35.

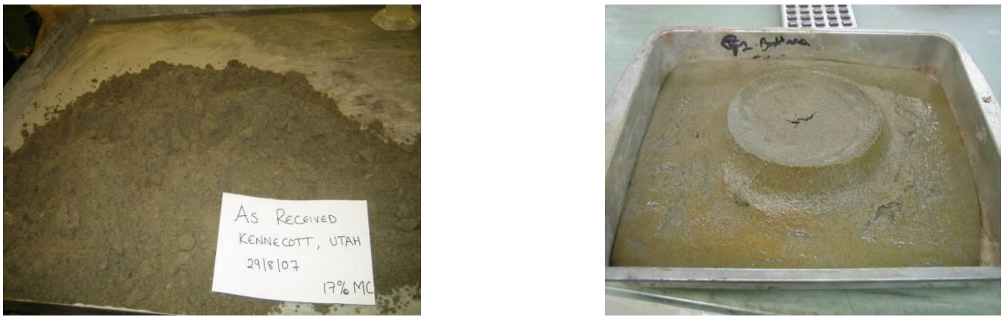


Fig. 2.31 Tailings at 17% moisture content liquefies when saturated (24% moisture content)

Fig. 2.32 Pullout of nail from tailings without electrokinetic treatment

Fig. 2.33 Post electrokinetic treatment, (a) showing cementation spreading from the anode, (b) nail pullout test

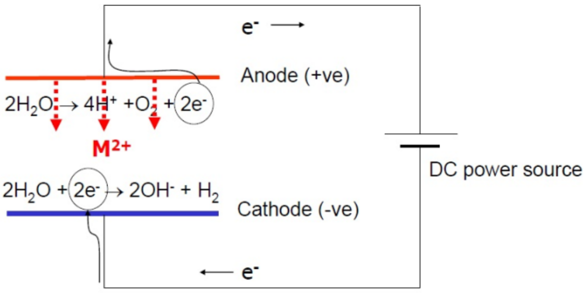


Fig. 2.34 Schematic of the function of short term sacrificial anodes

Fig. 2.35 Cementation of tailings radiating from the anode

2.5.6.9 eKG Application to Sports Turf

There are approximately 40,000 natural turf football pitches in the UK alone, with many more for other sports including rugby, golf, cricket, bowling and tennis. The most common problems afflicting the majority of these grounds are invariably related to one or more of the following factors: drainage, aeration, and nutrient concentrations. However, conventional maintenance regimes frequently prove inadequate in dealing with these problems in any long term sustainable way. EKG applied to sports turf can yield significant improvements in the physical performance and chemical conditions of sports surfaces and have the potential to improve reliability, performance and sustainability, Table 2.9 (Lamont-Black, 2003), (Lamont-Black et al 2006). The EKG turf system is illustrated in Figure 2.36. This is shown in the normal polarity mode of operation with the anode at the top. This is most effective for releasing oxygen to the root zone and for creating the maximum change in pore water pressure to improve surface shear strength and ball bounce following periods of heavy rain. Decompaction and increasing the water content of the near surface zone is achieved by polarity reversal.

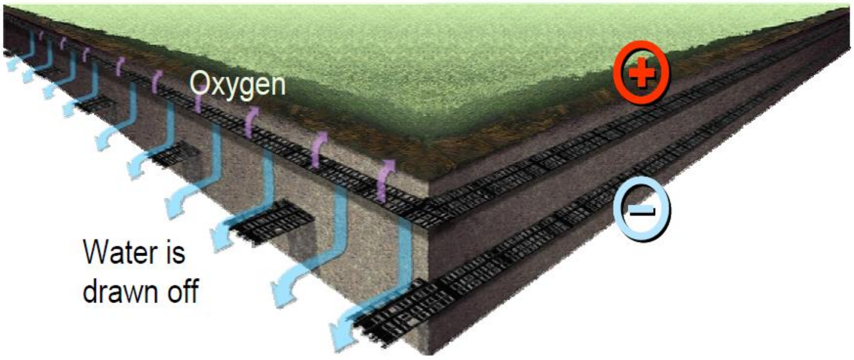


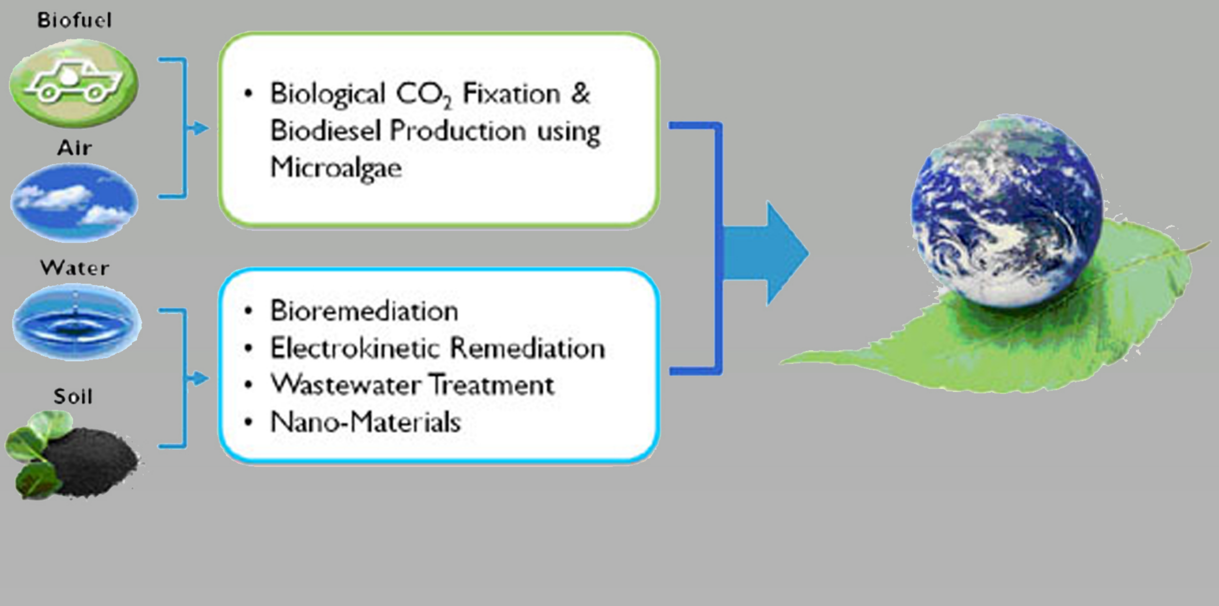
Fig. 2.36 Schematic of the Turf-EKG system

Table 2.9 Common problems associated with sports turfs and the mechanism and effects of treatment with EKGs

Problem	Electrokinetic process	Benefit to sports turf surfaces
Poor drainage	EO control of moisture content and drainage at cathode	No clogging, washing away, or loss in effectiveness. Macro pores not required and effects are uniform. Fine control of performance quality standards (PQS). Can incorporate soils with higher clay contents, requiring less application of fertilizer and irrigation. More sustainable.
Low oxygen content	Oxygen gas generated at anode. Also Decompaction is possible	Oxygen gas available throughout root zone. Substantially less thatch formation, increasing traction and general plant health. Uniform Decompaction leads to further aeration. Can incorporate soils with higher clay contents, requiring less application of fertilizer and irrigation. More sustainable.
Over compaction	Polarity reversal generates negative pore pressure and Decompaction	Decompaction is uniform, without formation of macro pores.
Low nutrient content	Higher percentage fines maybe possible	More nutrients retained, boosting plant health. Less frequent application of fertilizer. Lower maintenance costs.
“Foreign” invasion	Healthier plants more resistant to invasion	Less frequent application of biocides etc. Lower maintenance costs.
Low light levels	Healthier plants able to cope better with low light levels	Plants generally more robust.

CHAPTER 3

ELECTROKINETIC REMEDIATION OF NICKEL CONTAMINATED SOIL



- Biological CO_2 Fixation & Biodiesel Production using Microalgae

- Bioremediation
- Electrokinetic Remediation
- Wastewater Treatment
- Nano-Materials

3.1 INTRODUCTION

Heavy metal contamination of soil and groundwater is established and is a profound growing global problem. Methods for cleaning up contaminated sites involve either long-term containment systems or treatment systems. Containment technologies are interim solutions because of the possibility of future leaks. As the contaminants in such instances are only confined or immobilized, these sites are often abandoned or restricted for further use. In developed regions, the cost of the land or the fear of the neighborhood's reaction may result in unacceptable or politically biased technologies.

While most of the available techniques can be used for in-situ remediation of contaminated sandy soils, these techniques are not efficient in clayey soils. There is a lack of remediation techniques for the more impervious clayey soils when contaminated by heavy metals and/or hydrocarbons. The low hydraulic conductivity of such soils makes advective transport extremely difficult if not totally unfeasible. In electrokinetic treatment, electrical fields applied across a saturated soi1 mass result in electrolysis, transport of species by ionic migration, electroosmosis and diffusion. Electrokinetic remediation technique offers the opportunity to extract heavy metals form such soils with high plasticity, low CEC and low buffering capacity. The application of a low direct electrical (DC) current within the soil for an extended period of time results in several differences in medium, such as pH, purging solution concentrations and migration of the acid front into the soil causes complication on the nature of the clay chemistry as well as the process on the wholes. In spite of successful extraction of different species from the soil, the most important concern remaining still regarding the application of the technique in field is the high energy consumption and problems associated with the process. The purpose of the chapter here is to study the various factors associated with the process and provide a better understanding for effective contaminated site remediation.

3.2 AIMS

- The first aim/ objective was to design a simple yet robust apparatus that would allow ease of use in complex experiments.
- To study the use of electrokinetics as a tool for removal of heavy metal i.e. nickel from artificially spiked single mineral clay under low voltage DC supply.
- To study and evaluate different anodic and cathodic purging solutions for evaluation of removal efficiency.

- To optimize a combination of different anodic and cathodic purging solution at a particular given electrical gradient for maximum efficiency of removal.
- To study effect of configuration of electrodes i.e. electrode spacing at different applied voltage for selected combinations of purging solutions so as to maximize removal efficiency of nickel.
- To evaluate the effect of cross sectional area of soil sample i.e. cross sectional area of reactor to increase the removal of nickel for the optimized combination of purging solutions.
- To study effect of applied electric field i.e. voltage gradient for efficient mobilization and subsequent removal of nickel from soil.
- To assess the feasibility of applying the same combination of variables/ parameters of study on increased contaminant concentration, thereby offering a scope to improve the process over a larger range of concentration of nickel.
- Development of a multiple regression model taking into account the process as a whole with particular standpoints concerning the overall behaviour, applicability and overall mobilization of nickel.
- Development of an artificial neural network for the process using the experimental results obtained for training as well as a part of it for validation and testing.
- To study the sensitivity of the parameters under consideration for judging the efficiency of the developed neural network on the whole.

3.3 EXPERIMENTAL DEVELOPMENT AND MEASUREMENTS

3.3.1 Closed Electrokinetic Reactors

The electrokinetic remediation tests were conducted using the setup developed in house since no standard laboratory apparatus was available commercially for conduction of such electokinetic experiments or for the matter of fact the decontamination process of soils. The setup used in this study was developed with specific attention to concerns, such as consideration of size of soil cross section, electrode placing, collection of samples from different points along the sample, maintaining low current density, measurement of parameters during the performance of the experiment without affecting its outcome.

The setup was fabricated using polyvinyl chloride pipe of diameter 5.108 cm and 10.160 cm diameter of graded pressure capacity of 20 kg/cm^2 with flange end type connection being used to join the various compartments. The complete reactor was divided into three compartments i.e. anode cell, cathode cell and the central cell consisting of the soil sample. The anode and cathode cell were made of the same material with perspex perforated filter plates mounted in the flange itself with Whatman Filter pasted on the each of the filter plates. The anode and cathode cells so formed were then attached to the central cell which holds the contaminated soil using flange end connections. Higher capacity pipe was used in order to keep the pipe in horizontal condition without any deformation when filled with soil. This reactor was given necessary additional support externally without affecting the process so as to prevent it from bending which could increase the complexity of the process otherwise. Two different diameter pipes were used i.e. 5.08 cm diameter and 10.16 cm diameter (Fig. 3.1(a) and (b)) from which a total of seven reactors were fabricated. To study the electrode spacing four different length reactors were fabricated from 5.08 cm diameter pipe and three different length reactors from 10.16 cm diameter (Fig. 3.1(a) and (b)). Commercially available rubber packing and appropriately sized nut bolts are used to assemble the reactor to achieve water tightness. The two end sections each about 15cm long, housed the anode and cathode respectively. This arrangement of attachment of the anode and cathode compartments with flange end connections allowed the compaction, saturation and electrokinetic testing on the soil sample inside the same cell, with ease of assembly, eliminating the presence of trapped water in voids, which can occur at the interface between the compartments (Fig. 3.2). In the designed reactors, the artificially spiked soil was placed and tested in a horizontal position. Along the longitudinal axis of the central cell section, three pore sample ports were placed at equally spaced along the length of the central cell, for facilitation of collection of samples and for installation of pH probes and voltage measurement electrodes. The power supply used in the experiments was able to supply constant potential electrical field with a maximum range of 2A and 60V. All materials and fittings in contact with the contaminated soil and any chemical solution were made of PVC.

The only metal component used in the complete setup were the nut and bolts used to join the flange end connections to the central reactor. Figure 3.5 shows the complete setup in 3D. Carbon rods with 10mm diameter and 30cm long (Fig. 3.3) are selected for electrodes in this investigation. An open electrode arrangement was employed in the experiments to allow the movement of species and water in the electrode compartment. The electrode compartments and the soil compartments are separated using acrylic porous disk with a Whatman filter paper on either sides of it. The electrodes are placed in the compartments. The middle section of the reactor has three carbon needles inserted in the sample, to measure the electrical potential drop distribution along the sample using a designated attachment (Fig. 3.4).

3.3.2 Setup and Conduction of Experiments

Before using the reactor for experiments, they were checked for water tightness. Proper remedial measures were taken to avoid leakage, if any. In order to have a good distribution of nickel contaminant within the kaolinite sample, a predetermined amount of chloride salt of nickel was dissolved in an excess amount of distilled water. The kaolinite with the excess amount of solution was blended in batches and air dried. Kaolinite was spiked in batches of 20kg each with 41.75gm of nickel chloride salt being added so as to give 250 mg/kg concentration of nickel in soil. Higher concentrations of nickel were achieved by adding appropriate quantities of the salt to 20 kg batches of kaolinite. Kaolinite was compacted at 80% MDD on the wet side with hand compaction in the cylindrical reactor. The samples were placed for a week with the end caps to achieve proper saturations. After this the setup was put up for the process of electrokinetics by replacing the water in the end chambers with required purging solutions and placing of electrodes. Sacrificing carbon electrodes having 10 mm diameter and 30cm length were used for the application of voltage to the reactor, connected using a IS standard copper wise to the AC DC convertor unit or low frequency AC supply unit as required. Figure 3.6 shows the complete setup for electrokinetic procedure for remediation, grouting and dewatering procedure alongwith the measurements used during the complete procedure.

3.3.3 Observations

For all the experiments, readings of current, voltage (near anode, mid section, near cathode), and ambient temperature were taken at a fixed interval of time on a daily basis.

3.3.4 Collection of Samples

At the termination of each test, the specimen was removed from the cell and sliced into 3 sections. Soil from each segment was analyzed for water content and chemical analysis. Prior to testing the soil for chemical analysis, it was dried under controlled temperature upto 60°C and pulverized before being used for evaluating the nickel concentration.

3.4 EXPERIMENTAL SCHEDULE

The complete work for electrokinetic remediation was carried out on closed electrokinetic reactor as mentioned above in 3.3.1. The details of all experiments carried out with varying various parameters are tabulated in the tables with respect to the factor studied (Table 3.1). Chemical names of the purging solutions used are given below:

Chemical Form Used	Chemical Name
EDTA	Ethylene Diamine Tetra Acetic Acid
$NaNO_3$	Sodium Nitrate
Igepal CA 720	Igepal CA – 720, $4\text{-}(C_8H_{17})C_6H_4O(CH2CH_2O)_{11}CH_2CH_2OH$
Tween 80	Polyoxyethylene –(20)-sorbitan monolleate, $C_{64}H_{124}O_{26}$
NaCl	Sodium Chloride
$MgCl_2$	Magnesium Chloride
$CaCl_2$	Calcium Chloride
$HClO_4$	Perchloric Acid
$CH_3CH_2CH_2\text{-}COOH$	n – Butyric Acid (Butanoic Acid)
CH2-COOH HO-C-COOH CH2-COOH	Citric Acid (2-hydroxypropane-1,2,3-tricarboxylic acid)
CH_3COOH	Acetic Acid (Ethanoic Acid)

Experiments were performed using low frequency AC supply at 0.25Hz to 1Hz but have not been discussed since the results were not very satisfactory. Similarly work carried out on intermittent supply i.e. periodic supply did not give satisfactory results. These results have also not been considered in the mathematical modeling since the results caused the model to deviate and increased the amount of noise in the significance study.

Fig. 3.1(a) 5.08cm Diameter Models Of Different Lengths

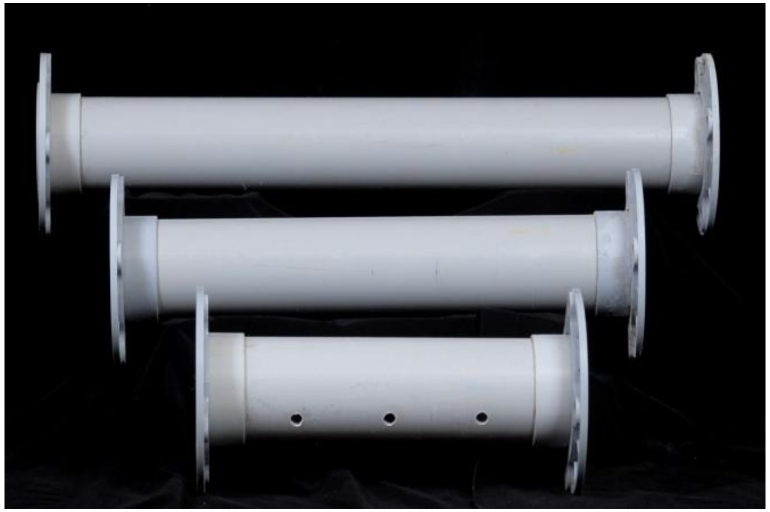


Fig. 3.1(b) 10.16cm Diameter Models Of Different Lengths

Fig 3.2 Anode & Cathode Cell

Fig.3.3 Electrodes

Fig 3.4 Attachment for Reading

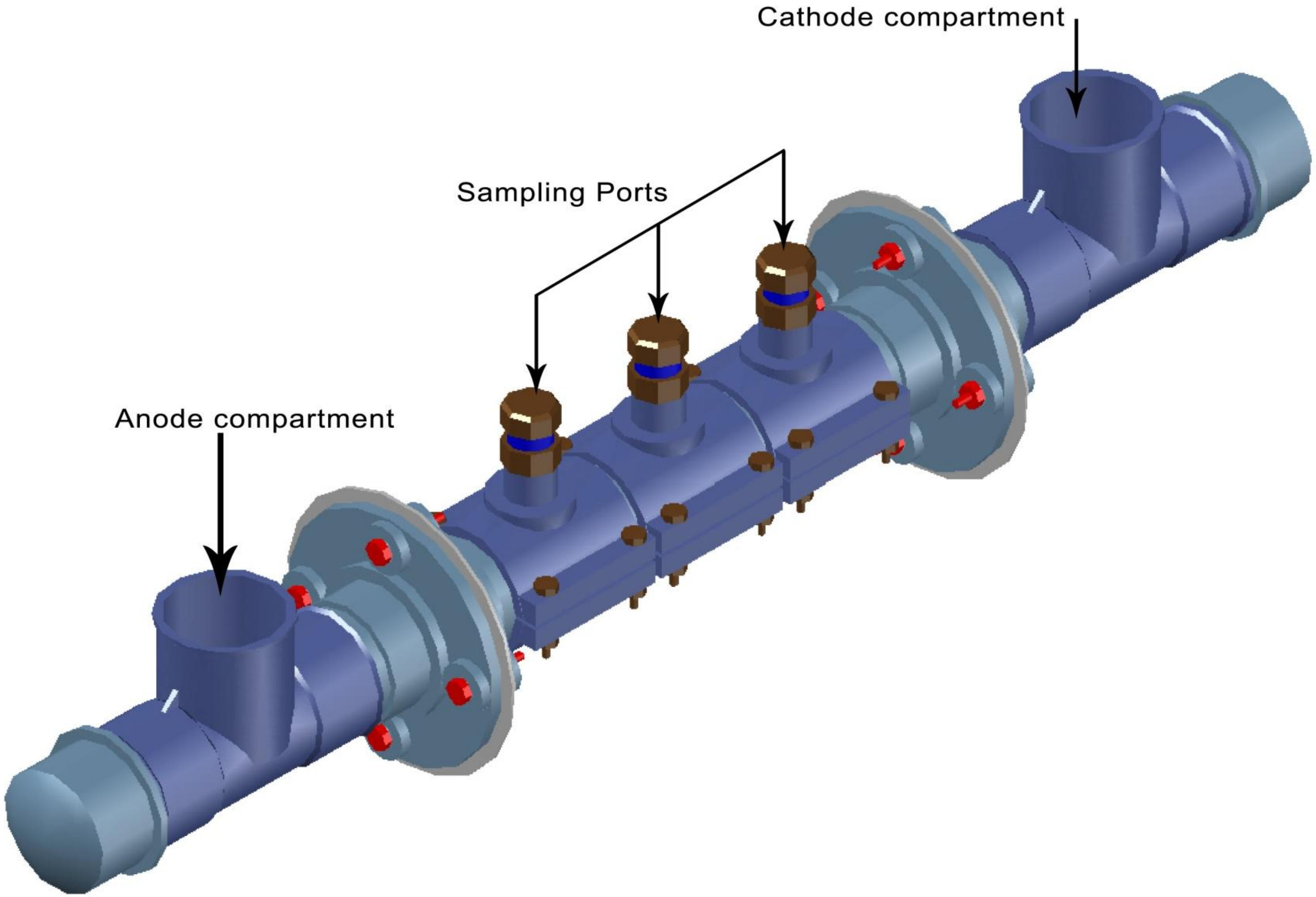


Fig. 3.5 Three Dimensional View of Closed Model Setup

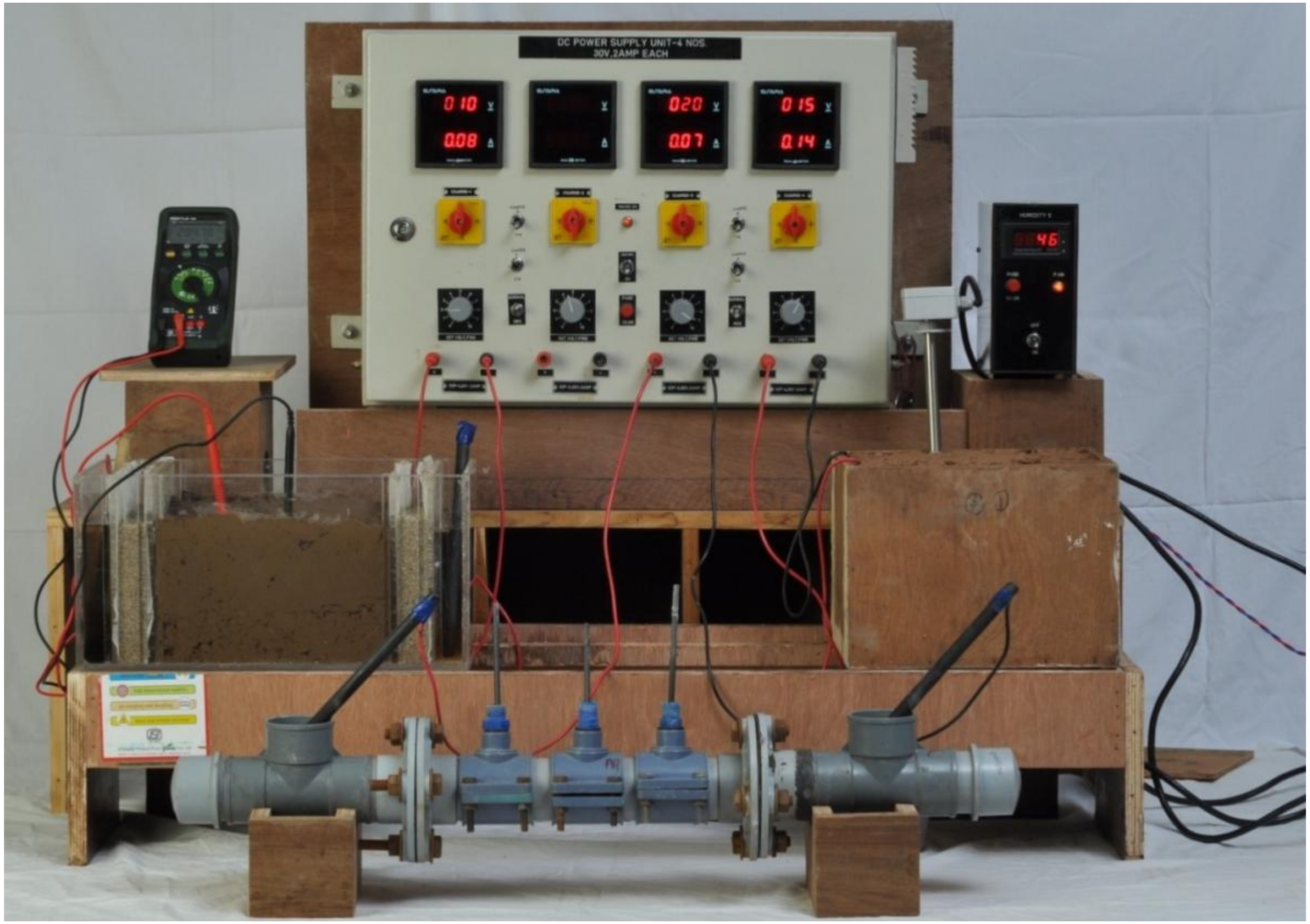


Fig. 3.6 Complete Setup for Electrokinetic Remediation

Table 3.1 Experimental Details for Electrokinetic Remediation of Nickel Contaminated Soil using Open Electrokinetic Reactor

Phase	Effect	Initial Concentration (mg/kg)	Cross Sectional Area of Reactor (cm^2)	Length of Reactor (cm)	Applied Voltage (V)	Cathode Solution	Anode Solution
1	Electrode Spacing	250	20.2683	34.50	25.00	0.1M EDTA	1.0M NaCl
		250	20.2683	45.72	25.00	0.1M EDTA	1.0M NaCl
		250	20.2683	68.58	25.00	0.1M EDTA	1.0M NaCl
		250	20.2683	91.44	25.00	0.1M EDTA	1.0M NaCl
		250	81.0732	45.72	35.00	0.1M EDTA	1.0M NaCl
		250	81.0732	68.58	35.00	0.1M EDTA	1.0M NaCl
		250	81.0732	91.44	35.00	0.1M EDTA	1.0M NaCl
		350	20.2683	34.50	25.00	0.1M EDTA	1.0M NaCl
		350	20.2683	45.72	25.00	0.1M EDTA	1.0M NaCl
		350	20.2683	68.58	25.00	0.1M EDTA	1.0M NaCl
		350	20.2683	91.44	25.00	0.1M EDTA	1.0M NaCl
		350	81.0732	45.72	35.00	0.1M EDTA	1.0M NaCl
		350	81.0732	68.58	35.00	0.1M EDTA	1.0M NaCl
		350	81.0732	91.44	35.00	0.1M EDTA	1.0M NaCl
		500	20.2683	34.50	25.00	0.1M EDTA	1.0M NaCl
		500	20.2683	45.72	25.00	0.1M EDTA	1.0M NaCl
		500	20.2683	68.58	25.00	0.1M EDTA	1.0M NaCl
		500	20.2683	91.44	25.00	0.1M EDTA	1.0M NaCl
2	Size of Reactor	250	20.2683	45.72	25.00	0.1M EDTA	1.0M NaCl
		250	20.2683	68.58	25.00	0.1M EDTA	1.0M NaCl
		250	20.2683	91.44	25.00	0.1M EDTA	1.0M NaCl
		250	81.0732	45.72	35.00	0.1M EDTA	1.0M NaCl
		250	81.0732	68.58	35.00	0.1M EDTA	1.0M NaCl
		250	81.0732	91.44	35.00	0.1M EDTA	1.0M NaCl

Table 3.1 Experimental Details for Electrokinetic Remediation of Nickel Contaminated Soil using Open Electrokinetic Reactor Cont'd

Phase	Effect	Initial Concentration (mg/kg)	Cross Sectional Area of Reactor (cm^2)	Length of Reactor (cm)	Applied Voltage (V)	Cathode Solution	Anode Solution
3	Voltage Gradient	250	20.2683	34.50	8.33	0.1M EDTA	1.0M NaCl
		250	20.2683	34.50	12.50	0.1M EDTA	1.0M NaCl
		250	20.2683	34.50	16.67	0.1M EDTA	1.0M NaCl
		250	20.2683	34.50	25.00	0.1M EDTA	1.0M NaCl
		250	20.2683	34.50	37.50	0.1M EDTA	1.0M NaCl
		350	20.2683	34.50	8.33	0.1M EDTA	1.0M NaCl
		350	20.2683	34.50	12.50	0.1M EDTA	1.0M NaCl
		350	20.2683	34.50	16.67	0.1M EDTA	1.0M NaCl
		350	20.2683	34.50	25.00	0.1M EDTA	1.0M NaCl
		350	20.2683	34.50	37.50	0.1M EDTA	1.0M NaCl
		350	20.2683	34.50	12.50	0.1M Tween 80	1.0M NaCl
		350	20.2683	34.50	16.66	0.1M Tween 80	1.0M NaCl
		350	20.2683	34.50	25.00	0.1M Tween 80	1.0M NaCl
		350	20.2683	34.50	37.50	0.1M Tween 80	1.0M NaCl
		350	20.2683	34.50	12.50	0.1M Igepal CA 720	1.0M NaCl
		350	20.2683	34.50	16.66	0.1M Igepal CA 720	1.0M NaCl
		350	20.2683	34.50	25.00	0.1M Igepal CA 720	1.0M NaCl
		350	20.2683	34.50	37.50	0.1M Igepal CA 720	1.0M NaCl
		500	20.2683	34.50	8.33	0.1M EDTA	1.0M NaCl
		500	20.2683	34.50	12.50	0.1M EDTA	1.0M NaCl
		500	20.2683	34.50	16.66	0.1M EDTA	1.0M NaCl
		500	20.2683	34.50	25.00	0.1M EDTA	1.0M NaCl
		500	20.2683	34.50	37.50	0.1M EDTA	1.0M NaCl
		500	20.2683	34.50	8.33	0.1M EDTA	1.0M $CaCl_2$
		500	20.2683	34.50	12.50	0.1M EDTA	1.0M $CaCl_2$
		500	20.2683	34.50	16.66	0.1M EDTA	1.0M $CaCl_2$
		500	20.2683	34.50	25.00	0.1M EDTA	1.0M $CaCl_2$
		500	20.2683	34.50	37.50	0.1M EDTA	1.0M $CaCl_2$

Table 3.1 Experimental Details for Electrokinetic Remediation of Nickel Contaminated Soil using Open Electrokinetic Reactor Cont'd

Phase	Effect	Initial Concentration (mg/kg)	Cross Sectional Area of Reactor (cm^2)	Length of Reactor (cm)	Applied Voltage (V)	Cathode Solution	Anode Solution
4	Anode Solution	250	20.2683	34.50	25.00	0.1M EDTA	1.0M NaCl
		250	20.2683	34.50	25.00	0.1M EDTA	1.0M $MgCl_2$
		250	20.2683	34.50	25.00	0.1M EDTA	1.0M $CaCl_2$
		250	20.2683	34.50	25.00	0.1M EDTA	0.1M $HClO_4$
		250	20.2683	34.50	25.00	0.1M EDTA	1.0M $HClO_4$
		250	20.2683	34.50	25.00	0.1M EDTA	1.0M $C_4H_8O_2$
		250	20.2683	34.50	25.00	0.1M EDTA	1.0M Citric Acid
		250	20.2683	34.50	25.00	0.1M EDTA	1.0M Acetic Acid
		250	20.2683	34.50	25.00	1.0M $NaNO_3$	1.0M NaCl
		250	20.2683	34.50	25.00	1.0M $NaNO_3$	1.0M $MgCl_2$
		250	20.2683	34.50	25.00	1.0M $NaNO_3$	1.0M $CaCl_2$
		250	20.2683	34.50	25.00	1.0M $NaNO_3$	0.1M $HClO_4$
		250	20.2683	34.50	25.00	1.0M $NaNO_3$	1.0M $HClO_4$
		250	20.2683	34.50	25.00	1.0M $NaNO_3$	1.0M n-Butyric Acid
		250	20.2683	34.50	25.00	1.0M $NaNO_3$	1.0M Citric Acid
		250	20.2683	34.50	25.00	1.0M $NaNO_3$	1.0M Acetic Acid
		350	20.2683	34.50	25.00	0.1M EDTA	1.0M NaCl
		350	20.2683	34.50	25.00	0.1M EDTA	0.1M $HClO_4$
		350	20.2683	34.50	25.00	0.1M EDTA	1.0M $HClO_4$
		350	20.2683	34.50	25.00	0.1M EDTA	1.0M n-Butyric Acid
		350	20.2683	34.50	25.00	1.0M $NaNO_3$	1.0M NaCl
		350	20.2683	34.50	25.00	1.0M $NaNO_3$	0.1M $HClO_4$
		350	20.2683	34.50	25.00	1.0M $NaNO_3$	1.0M $HClO_4$
		350	20.2683	34.50	25.00	1.0M $NaNO_3$	1.0M n-Butyric Acid

Table 3.1 Experimental Details for Electrokinetic Remediation of Nickel Contaminated Soil using Open Electrokinetic Reactor Cont'd

Phase	Effect	Initial Concentration (mg/kg)	Cross Sectional Area of Reactor (cm^2)	Length of Reactor (cm)	Applied Voltage (V)	Cathode Solution	Anode Solution
4	Anode Solution	500	20.2683	34.5	25.00 V	0.1M EDTA	1.0M NaCl
		500	20.2683	34.5	25.00 V	0.1M EDTA	1.0M $MgCl_2$
		500	20.2683	34.5	25.00 V	0.1M EDTA	1.0M $CaCl_2$
		500	20.2683	34.5	25.00 V	0.1M EDTA	0.1M $HClO_4$
		500	20.2683	34.5	25.00 V	0.1M EDTA	1.0M $HClO_4$
		500	20.2683	34.5	25.00 V	0.1M EDTA	1.0M n-Butyric Acid
		500	20.2683	34.5	25.00 V	0.1M EDTA	1.0M Citric Acid
		500	20.2683	34.5	25.00 V	0.1M EDTA	1.0M Acetic Acid
		500	20.2683	34.5	25.00 V	1.0M $NaNO_3$	1.0M NaCl
		500	20.2683	34.5	25.00 V	1.0M $NaNO_3$	1.0M $MgCl_2$
		500	20.2683	34.5	25.00 V	1.0M $NaNO_3$	1.0M $CaCl_2$
		500	20.2683	34.5	25.00 V	1.0M $NaNO_3$	0.1M $HClO_4$
		500	20.2683	34.5	25.00 V	1.0M $NaNO_3$	1.0M $HClO_4$
		500	20.2683	34.5	25.00 V	1.0M $NaNO_3$	1.0M n-Butyric Acid
		500	20.2683	34.5	25.00 V	1.0M $NaNO_3$	1.0M Citric Acid
		500	20.2683	34.5	25.00 V	1.0M $NaNO_3$	1.0M Acetic Acid
5	Cathode Solution	250	20.2683	34.5	25.00 V	0.1M EDTA	1.0M NaCl
		250	20.2683	34.5	25.00 V	0.1M Tween 80	1.0M NaCl
		250	20.2683	34.5	25.00 V	0.1M Igepal CA 720	1.0M NaCl
		250	20.2683	34.5	25.00 V	1.0M H_3PO_4	1.0M NaCl
		250	20.2683	34.5	25.00 V	1.0M $NaNO_3$	1.0M NaCl
		350	20.2683	34.5	25.00 V	0.1M EDTA	1.0M NaCl
		350	20.2683	34.5	25.00 V	0.1M Tween 80	1.0M NaCl
		350	20.2683	34.5	25.00 V	0.1M Igepal CA 720	1.0M NaCl

3.5 EXPERIMENTAL RESULTS AND DISCUSSION

In order to ensure the accuracy and reproducibility of the results, all the experiments were conducted in replicates. Uniform testing conditions were maintained in all the experiments by properly checking the electrokinetic reactors, electrode assemblies and electrode reservoirs. During the analysis of nickel, care was taken to ensure that the samples were checked for accuracy by regularly calibration of all the instruments used during the complete study.

3.5.1 Effect of Electrode Spacing

Analysis: To study the effect of electrode spacing on remediation of nickel contaminated soil, seven set of experiments are performed during the course of study; i.e. for 10.16 cm diameter of reactor electrode spacing = 45.72 cm, 68.58 cm, 91.44 cm and for 5.08 cm diameter of reactor electrode spacing = 34.5 cm, 45.72 cm, 68.58 cm, 91.44 cm. It is concluded that highest percentage Ni removal is attributed to nearly 87.88% in the reactor of 5.08 cm diameter. Fig. 3.7 shows that the percentage Ni removal decreases from 87.88% to 66.76% with increase in electrode spacing in reactor with 5.08cm diameter (cross sections area of reactor = 20.26 cm^2). For the 10.16 cm (cross sectional area of reactor = 81.07 cm^2) diameter of reactor, percentage Ni removal decreased from 87.84% to 76.63% with increase in electrode spacing. Figure 3.8 and 3.9 shows the percentage Ni removal for both sizes of reactors at different electrode spacing with initial concentration of 350 and 500 mg/kg. The percentage Ni removal varied from 81.745 to 68.93% in case of 5.08cm diameter reactor and it varied from 84.36% to 74.34% for reactor diameter of 10.16 cm in case of initial concentration of 350 mg/kg. Initial nickel concentration of 500 mg/kg was studied on 5.08cm diameter reactor, wherein the percentage Ni removal varied from 87.03% to 67.88%. Tests on electrode spacing of 45.72 cm showed higher value as opposed to the usual 34.5 cm electrode spacing. The trend of higher percentage Ni removal at lower electrode spacing and higher cross sectional area is followed generally in both the cases.

Discussion: As expected, more rapid and greater movement of nickel occurred with the 34.5 cm closer electrode spacing. The difference is attributed to the greater electric potential gradient with closer electrode spacing. Lower electrode spacing improves the rate of flow, lowers the contact resistance and reduces the voltage drop. The higher efficiency is also due to higher electroosmotic drainage being proportional to the effective voltage which is higher for lower electrode spacing.

3.5.2 Effect of Size of Reactor

Analysis: To study the effect of size of reactor on remediation of nickel contaminated soil two experiments; (size - 5.08 cm, and 10.16 cm diameter of reactor at 45.72 cm, 68.58cm and 91.44cm electrode spacing) were conducted. It is observed that the highest percentage Ni removal is attributed to nearly 87.84% in 10.16 cm diameter reactor whereas it is

86.82% for the 5.08 cm diameter reactor for 45.72cm spacing, it is 77.57% and 81.22% for 68.58cm, and 66.76% and 76.63% for 91.44cm (Fig. 3.10).

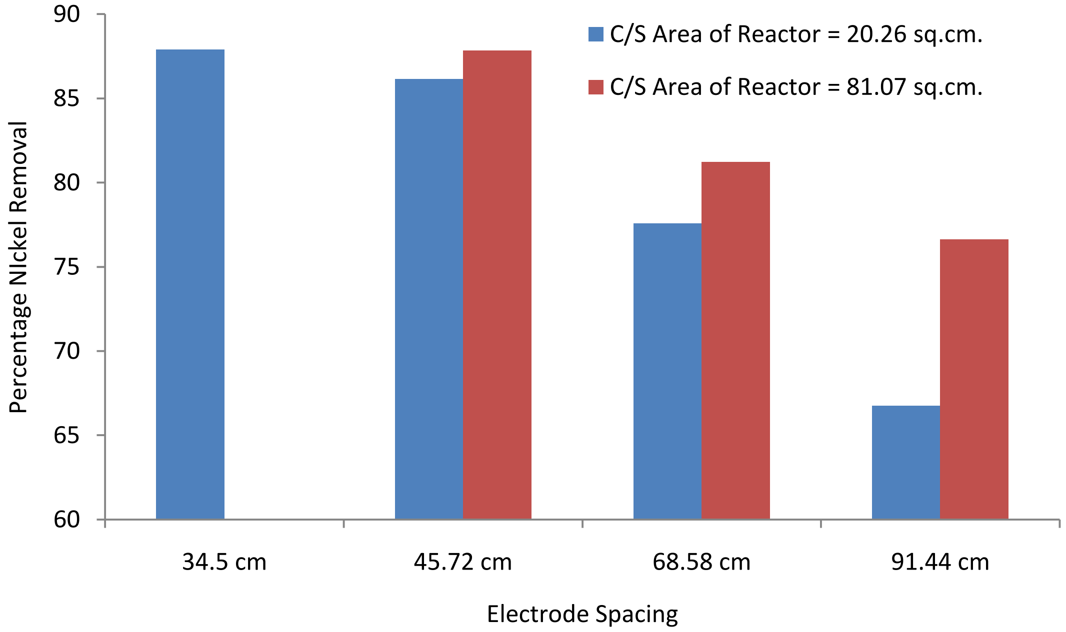


Fig. 3.7 Percentage Ni removal (Effect of Electrode Spacing), Initial Concentration = 250 mg/kg, Cathode Solution = 0.1M EDTA, Anode Solution = 1.0M NaCl

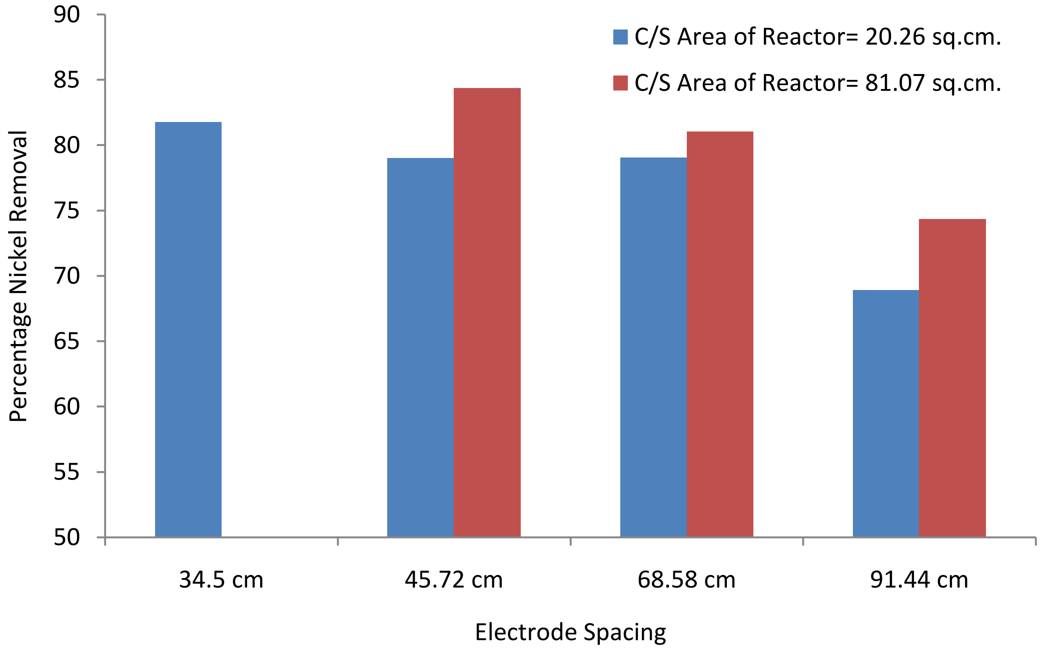


Fig. 3.8 Percentage Ni removal (Effect of Electrode Spacing), Initial Concentration = 350 mg/kg, Cathode Solution = 0.1M EDTA, Anode Solution = 1.0M NaCl

Discussion: The observed increase in efficiency of Ni removal with increase in cross sectional area may be due to the decreased resistance offered by the soil to the transport of the base front in the soil is reduced which increases the effectiveness of the remediation

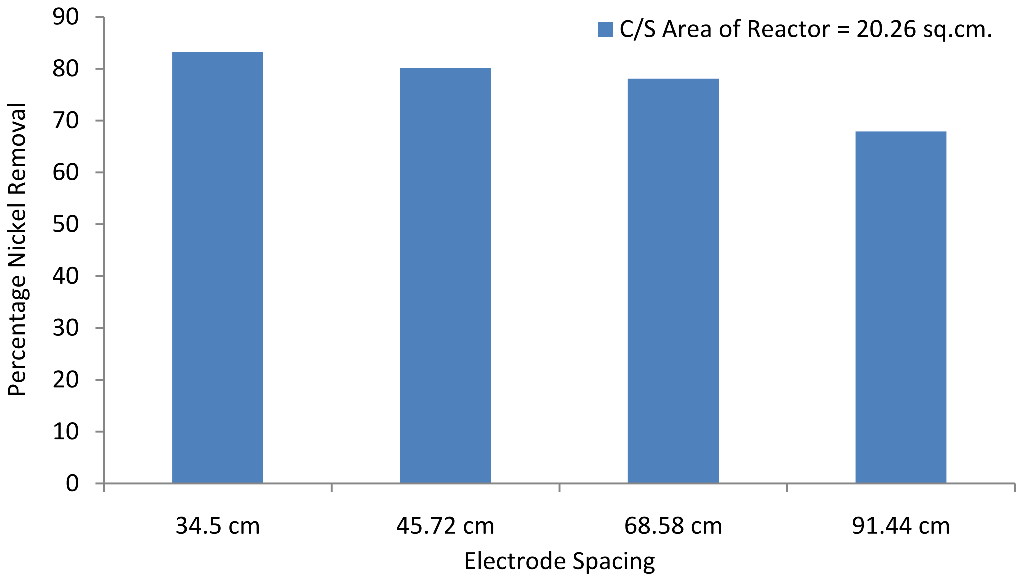


Fig. 3.9 Percentage Ni removal (Effect of Electrode Spacing), Initial Concentration = 500 mg/kg, Cathode Solution = 0.1M EDTA, Anode Solution = 1.0M NaCl, Applied Voltage = 25.00V

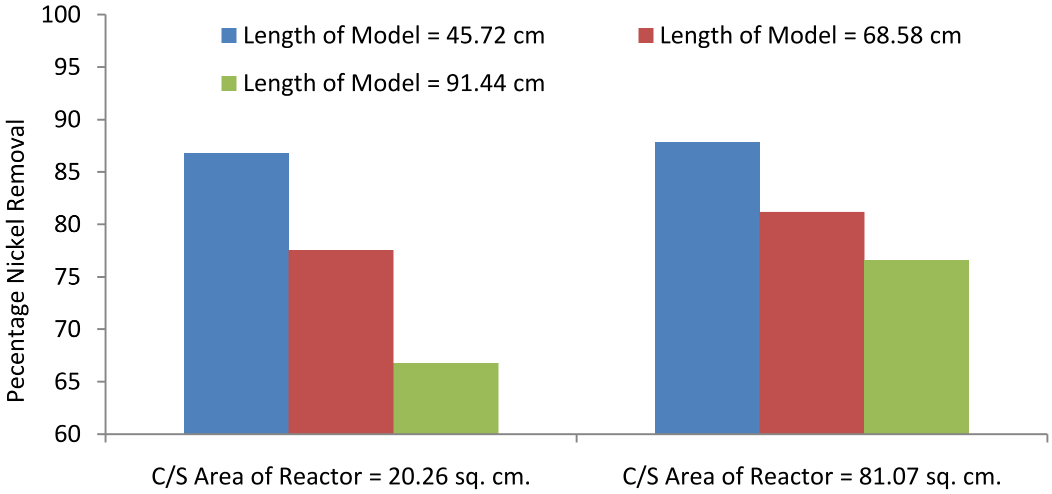


Fig. 3.10 Percentage Ni removal (Effect of Size of Reactor), Initial Concentration = 250 mg/kg, Cathode Solution = 0.1M EDTA, Anode Solution = 1.0M NaCl, Applied Voltage = 25.00V

3.5.3 Effect of Voltage Gradient

Analysis: Voltage gradient was studied over a wide range from 8.33V to 37.5V being applied at an electrode spacing of 34.5cm with cross sectional area of 20.26 cm^2. Figure 3.11 shows the percentage Ni removal for the case of 250 mg/kg concentration. The highest percentage Ni removal observed was 91.43% for applied voltage of 37.5V, with the removal percentage reducing to 71.07% at 8.33V with 0.1M EDTA at cathode and 1.0M NaCl at anode. For the same combination of purging solution, the removal efficiency reduced to 83.41% for 37.5V to 73.71% at 8.33V for 350mg/kg initial concentration, whereas it was 84.06% for 37.5V to 72.17% for 8.33V for 500mg/kg initial concentration (Fig. 3.12 and 3.13). The study was enhanced by varying the cathode and anode purging solution i.e. the use of Tween 80 and Igepal CA 720 at cathode instead of EDTA and used of $CaCl_2$ instead of NaCl at the anode, to see if the variation and the trend followed was similar to that seen in case of 0.1M EDTA and 1.0M NaCl. The study was also required for mathematical modeling where variation for each parameter is necessary.

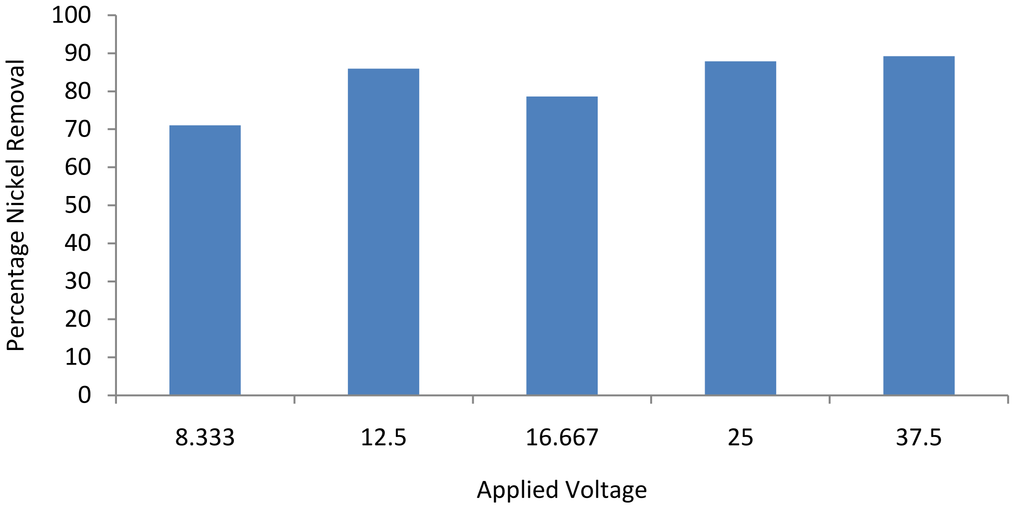


Fig. 3.11 Percentage Ni removal (Effect of Voltage Gradient), Initial Concentration = 250 mg/kg, Cathode Solution = 0.1M EDTA, Anode Solution = 1.0M NaCl, Applied Voltage = 25.00V, C/S Area of Reactor = 20.26cm^2, Electrode spacing = 34.5 cm

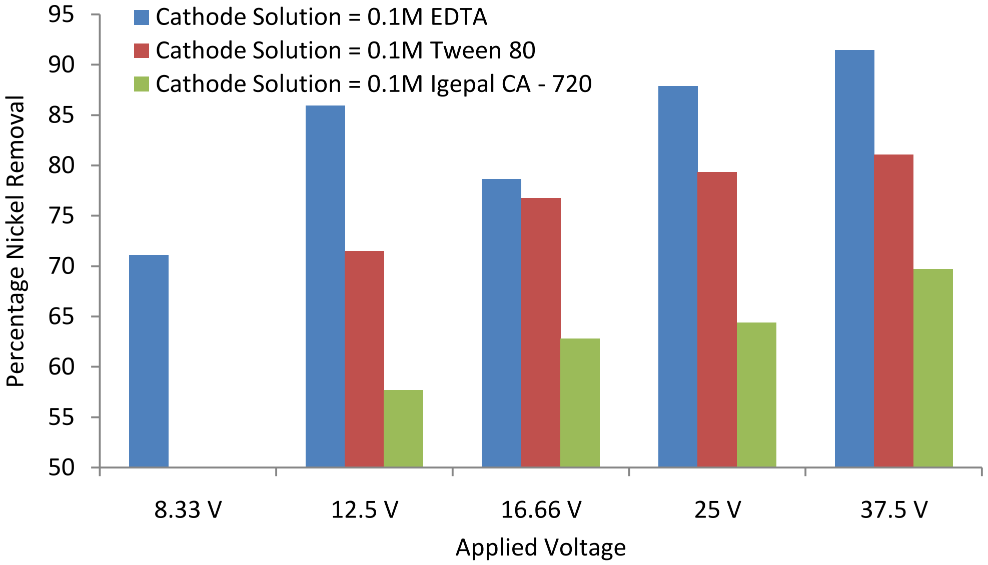


Fig. 3.12 Percentage Ni removal (Effect of Voltage Gradient), Initial Concentration = 350 mg/kg, Anode Solution = 1.0M NaCl, Applied Voltage = 25.00V, C/S Area of Reactor = 20.26cm^2, Electrode spacing = 34.5 cm

Discussion: Significant migration of nickel occurred from anode to cathode in all experiments. When the applied voltage was increased for the given electrode spacing, the electric current also increases due to an increase in the ionic strength in the electrode solutions and more ions entering into the soil from the respective electrodes. The increased currents results in increased as well as sustain electro-osmotic flow during the remediation process. The increased current also may have caused the increase in the rate of electrolysis reactions, with H^+ ions being generated at the anode and OH^- ions generated at the cathode. These ions, being constantly generated, possess high mobility into the soil. Additionally higher voltage application may have caused the reduction in the pH of the soil, resulting in greater migration of the nickel from the soil to the cathode compartment where it was precipitated. Due to the inflow of acidic solution, causes the pH to be lowered which helps the addition dissolution of the metal and compound formation with higher current values. The higher applied voltage causes higher ionic movement but as the time progresses i.e. period of application of supply, it may lead to faster depletion of the ions. The increase in the initial concentration of the metal ions may have resulted in the localized accumulation of these ions within the soil matrix. This in turn results in diminishing the soil water due to increase in the temperature of the soil matrix inducing thermal gradients, which hinder the electrokinetic process as a whole. The increase in the temperature also causes reduction in the water content of the matrix which will increase the resistance of the soil further reducing the current flow, which results in the reduction of removal efficiency. This may be the reason that higher initial concentration shows lower percentage Ni removal.

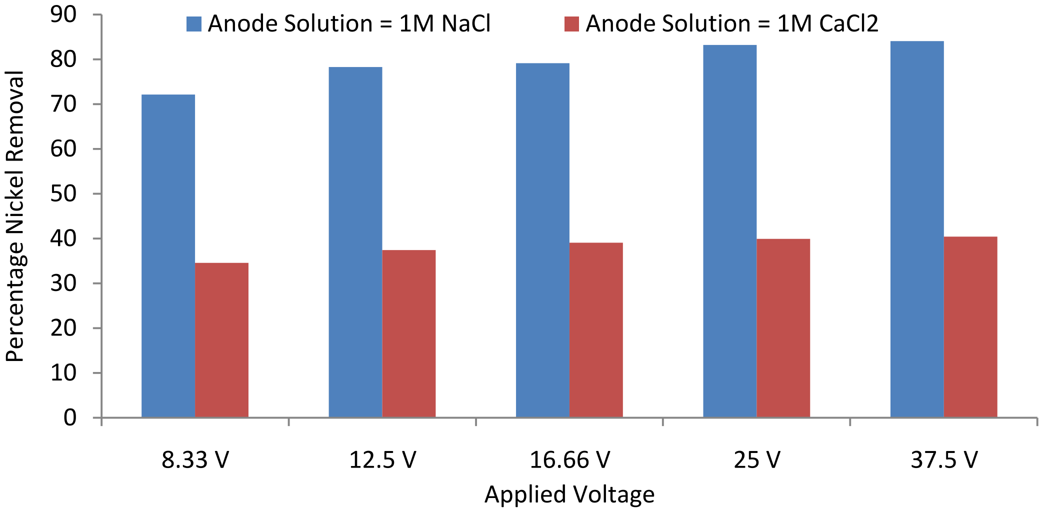


Fig. 3.13 Percentage Ni removal (Effect of Voltage Gradient), Initial Concentration = 500 mg/kg, Cathode Solution = 0.1M EDTA, Applied Voltage = 25.00V, C/S Area of Reactor = 20.26cm^2, Electrode spacing = 34.5 cm

3.5.4 Effect of Anode Solution

Analysis: The study investigated the feasibility of using different anodic purging solutions in combination with either 0.1M EDTA and 1M $NaNO_3$ at the three initial concentrations of 250, 350 and 500 mg/kg respetively. The different anodic solution studied were 1M NaCl, 1M $MgCl_2$, 1M $CaCl_2$, 0.1M and 1M Perchloric Acid, 1M N-butyric acid, 1M Citric Acid and 1M Acetic Acid. When using EDTA as the cathodic purging solution, the percentage Ni removal varied from 87.2% for 1M NaCl, 76.66% for 1M $MgCl_2$, 73.88% for 1M perchloric acid, 72.61% for 0.1M perchloric acid, 71.2% for

1M acetic acid, 68.8% for 1M n-butyric acid, 64.29% for 1M citric acid and reduced drastically down to 32.84% for 1M $CaCl_2$ for 250 mg/kg initial concentration. In case when 1M $NaNO_3$, was used as cathodic solution at the same initial concentration of nickel, the percentage varied from 69.32% being maximum for 1M NaCl to 22.17% being the minimum percentage Ni removal when using 1M $CaCl_2$ (Fig. 3.14). Figure 3.15 shows the plot for initial concentration of 350mg/kg where 0.1M EDTA gave percentage Ni removal of 81.74% with 1M NaCl down to 65.28% with 1M n-butyric acid, whereas the similarly percentage Ni removal with 1M $NaNO_3$ was 67.21% and 60.48% respectively. The percentage Ni removal of nickel at 500mg/kg initial concentration with 0.1M EDTA at the cathode varied from 80.73% for 1.0M NaCl anode solution and reduced to 31.18% for 1M $CaCl_2$ at the anode (Fig. 3.16).

Discussion: The removal efficiency of Ethylenediamine tetra acetic acid (EDTA) was quite good with all anodic purging solutions used. This is because Ethylenediamine tetra acetic acid is hexdentate ligand that has six electron pairs that are capable of being shared with one or more metal cations. When EDTA was replaced with $NaNO_3$ it gives low removal efficiency with all the anodic solutions, even when the solution is 10 times stronger. The reason behind is that the nitrate ions do not easily combine with heavy metals under higher pH value. The reaction for compound formation requires low pH which is difficult to maintain. Sodium chloride with EDTA seemed to be the best combination for nickel removal. The sodium ion from sodium chloride alongwith EDTA forms a soluble complex with nickel ion which is stable. On the other hand when magnesium or $CaCl_2$ is used as an anodic purging solution similar percentage of removal is not observed. In fact, use of $CaCl_2$ shows the minimum removal of nickel. The use of $CaCl_2$ leads to the precipitation of the calcium at the cathode which gets magnified with the presence of EDTA at the cathode compartment. This leads to an abundance of the negatively charged complexes and their subsequent transport towards the anode, creating a deficiency of anions near the cathode section. The precipitation which takes place at the cathode forms a precipitation barrier at the section causing hindrance to the movement of the nickel.

The removal efficiency of lower concentration of perchloric acid is lower as compared to its higher concentration; this may be due to the lower pH values at higher concentration which lead to the metals existing mostly in the aqueous phase only. The chelating ability of EDTA then contributes to the removal of metals. The use of acetic acid in anode aqueous solutions partially dissociates it into the hydrogen ion H^+ and the acetate ion $CH3COO^-$. The H^+ ions produced can decrease the solution pH and dissolve metal precipitates, while acetate ions may complex with other metal ions that are present in the solution. However, the stability constant of acetate-metal complexes is low, and, therefore, acetate-metal complexation is usually not very significant, which reasons out the lower percentage Ni removal of nickel.

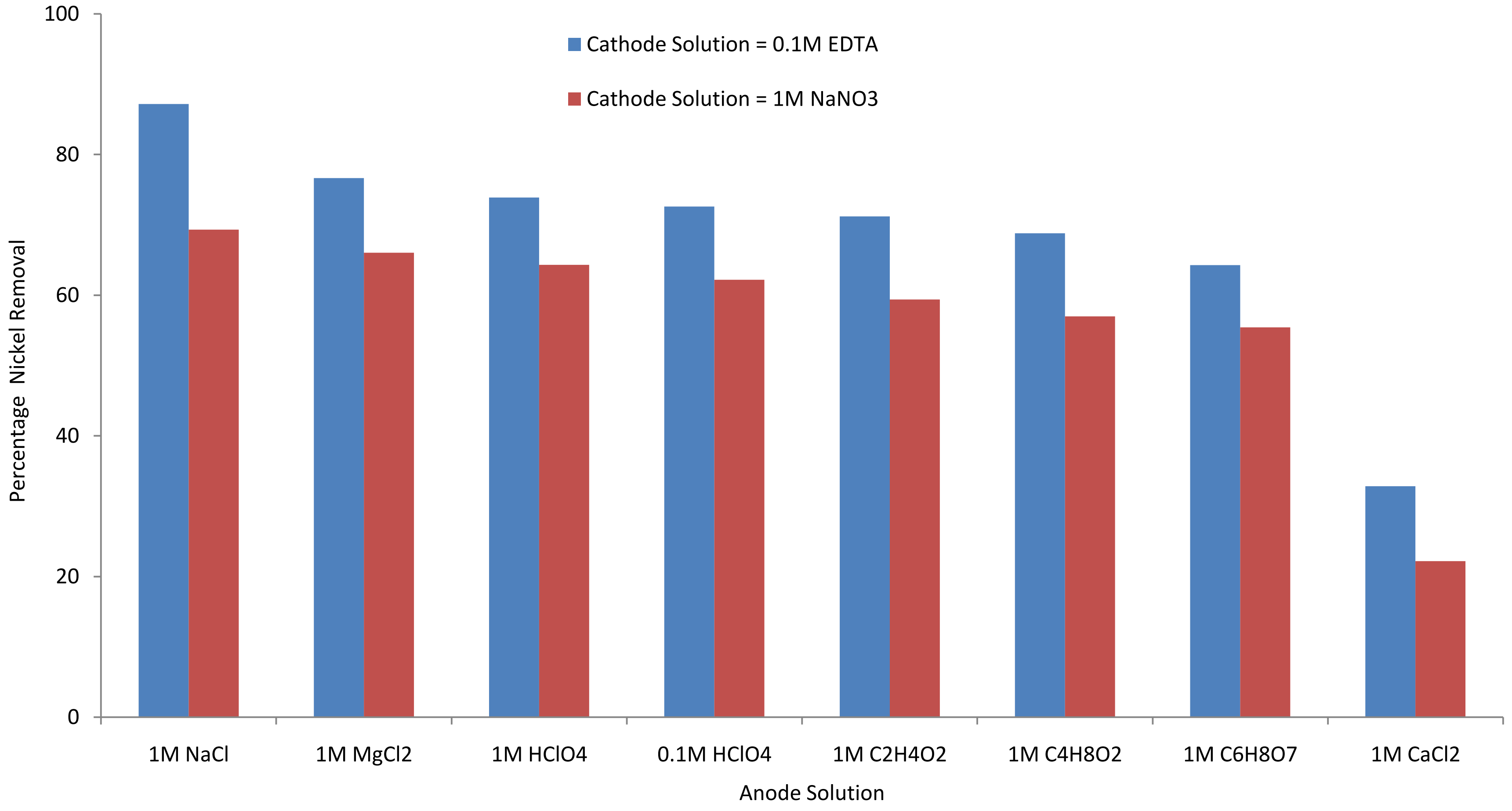


Fig. 3.14 Percentage Ni removal (Effect of Anode Solution), Initial Concentration = 250 mg/kg, Applied Voltage = 25.00V, C/S Area of Reactor = 20.26cm^2, Electrode spacing = 34.5 cm

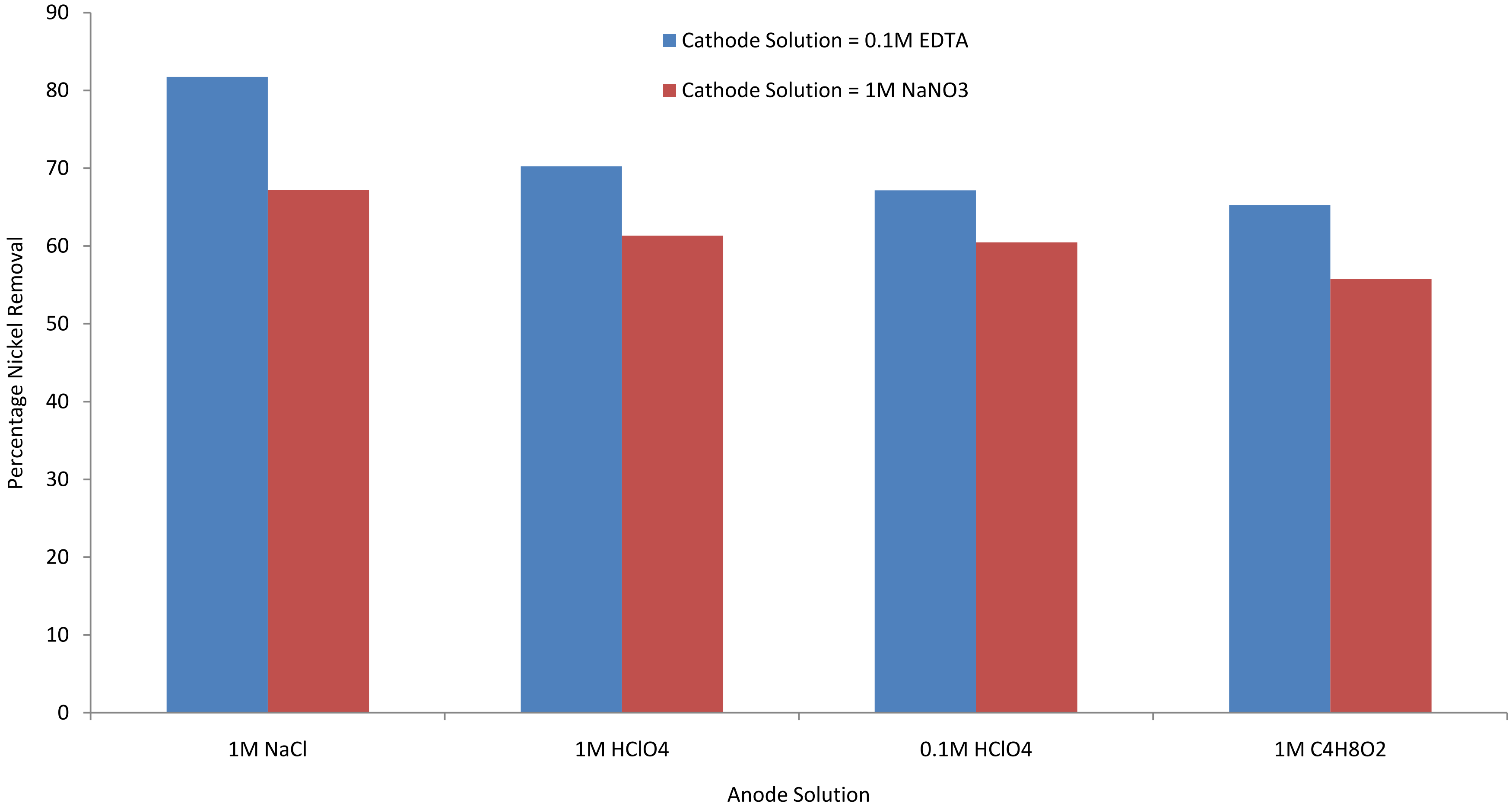


Fig. 3.15 Percentage Ni removal (Effect of Anode Solution), Initial Concentration = 350 mg/kg, Applied Voltage = 25.00V, C/S Area of Reactor = 20.26cm^2, Electrode spacing = 34.5 cm

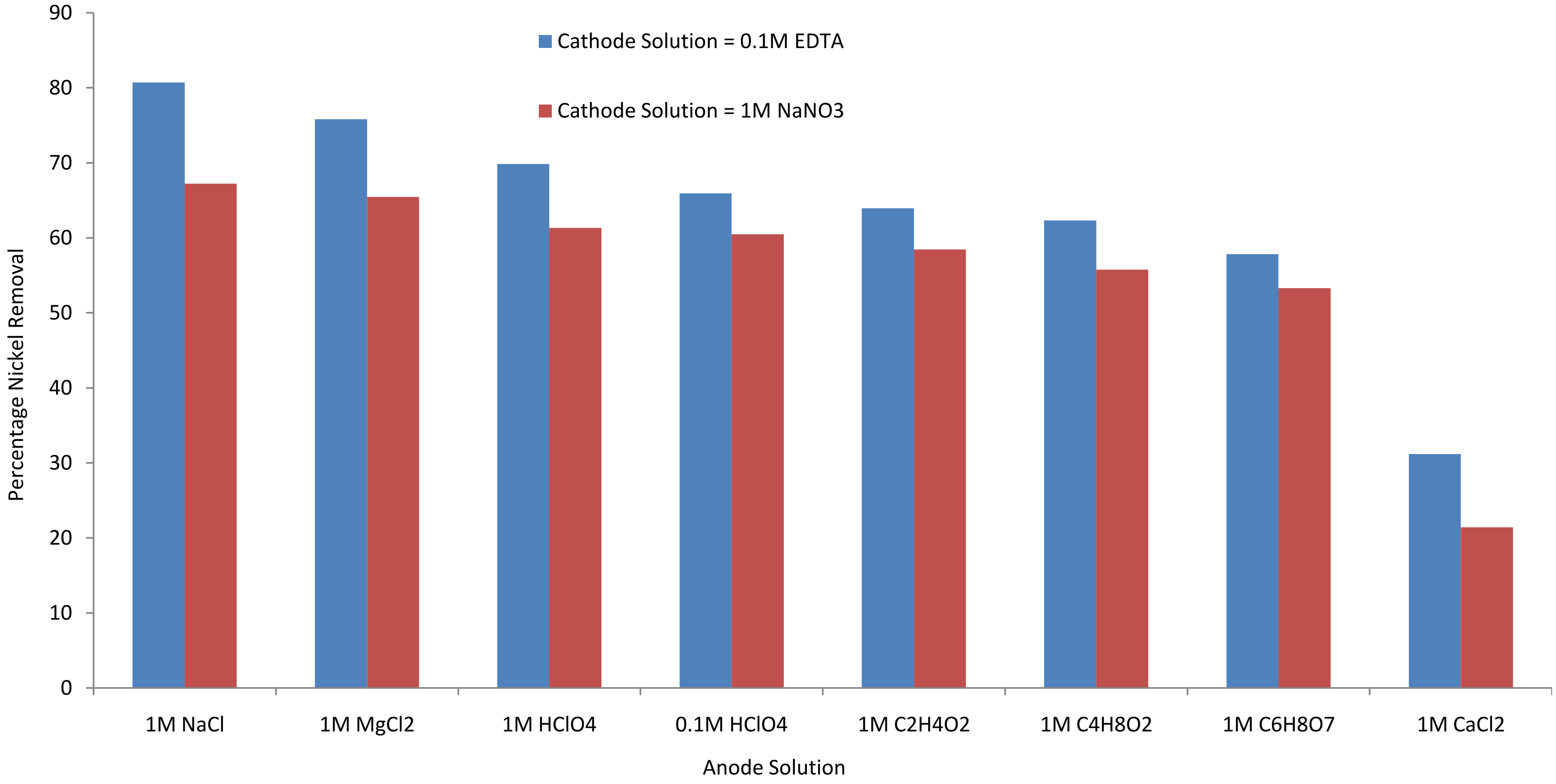


Fig. 3.16 Percentage Ni removal (Effect of Anode Solution), Initial Concentration = 350 mg/kg, Applied Voltage = 25.00V, C/S Area of Reactor = 20.26cm^2, Electrode spacing = 34.5 cm

The nickel removal efficiency of citric acid was found to be low as compared to other solution except $CaCl_2$. Citric acid forms mononuclear, binuclear, or polynuclear and bi-, tri-, and multidentate complexes, depending on the type of the available metallic ion, with nickel it form a bidentate mono nuclear complex with the two carboxyl acid groups of the citric acid molecule. Moreover, when a strong complexing agent like the citric acid was used, a greater pollutant removal would be expected, but it is interesting to note that it occurs the opposite phenomena: nickel removal decrease considerably, which may be associated to a low mobility of the nickel-citrate complex, and a lower dissolution due to the nickel-citrate complex sorption on soil surface, resulting to lower removal efficiency. From the above discussion, it can be proposed that electrokinetic nickel removal taking place in samples with the different anodic purging solutions, it is not only function of nickel solubility, but also of some other phenomena in which the soil particle interaction with its surroundings, and the interfacial electric field, should be playing a decisive role on the observed response.

3.5.5 Effect of Cathode Solution

Analysis: This study was carried out at initial concentration of 250 and 350mg/kg by using 1M NaCl as the anodic solution and varying the cathodic solutions i.e. 0.1M EDTA, 0.1M Tween 80, 0.1M Igepal CA-720, 1M Ortho Phosphoric Acid and 1M $NaNO_3$. Figure 3.17 shows plot for percentage Ni removal at 250 mg/kg initial concentration, with 1M NaCl at anode and varying cathodic purging solutions. The percentage Ni removal was 87.5% with 0.1M EDTA, 84.82% for 0.1M Tween 80, 75.24% with 0.1M Igepal CA – 720, 78.99% with 1M o-Phosphoric Acid and 82.31% with 1M $NaNO_3$. When the initial concentration is increased to 350mg/kg, the percentage Ni removal was 81.74% for 0.1M EDTA, 79.32% with 0.1M Tween 80 and 64.38% for 0.1M Igepal CA – 720 (Fig. 3.18).

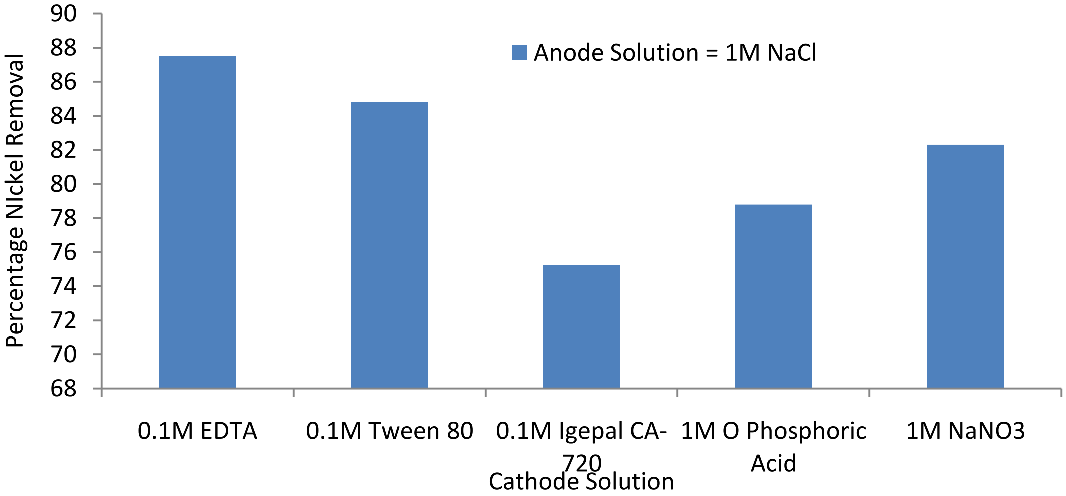


Fig. 3.17 Percentage Ni removal (Effect of Cathodic Solution), Initial Concentration = 250 mg/kg, Anode Solution = 1.0M NaCl, Applied Voltage = 25.00 V, C/S Area of Reactor = $20.26 cm^2$, Electrode spacing = 34.5 cm

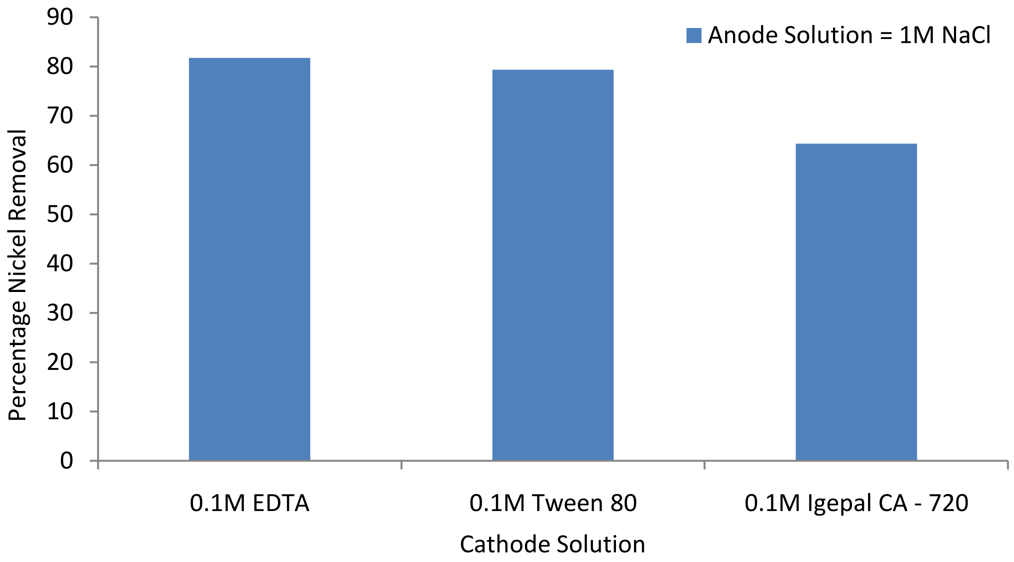


Fig. 3.18 Percentage Ni removal (Effect of Cathodic Solution), Initial Concentration = 350 mg/kg, Anode Solution = 1.0M NaCl, Applied Voltage = 25.00 V, C/S Area of Reactor = 20.26 cm^2, Electrode spacing = 34.5 cm

Discussion: Ethylenediaminetetraacetic acid (EDTA) is a highly branched, high molecular weight acidic compound. It has an ability to form a strong water soluble chelate with metals. It is a tetraprotic acid with dissociate into a wide variety of species such as H_3Y^-, H_2Y^{2-}, HY^{3-}, and Y^{4-}. Each EDTA ion can coordinate bond to a metal at six different sites, namely each of the four acetate sites and two nitrogen sits, which have free electron pairs available for coordinate bond formation. The numerous coordination sites inherent to EDTA ions create complexes that are highly stable and favourable to chelation technology. When a metal cation comes into contact with an EDTA ion, numerous complexes can result. A complex of the form MY, a protonated MHY complex, Hydroxocomplex $MY(OH)_n$, and a mixed complex MYX can result, where X in a unidentate ligand. The simplified complexation reactors are shown as below:

$$\boldsymbol{M^{n+} + Y^{4-} \Leftrightarrow MY^{n-4}}$$

$$\boldsymbol{M^{n+} + H^{+} + Y^{4-} \Leftrightarrow MHY^{n-3}}$$

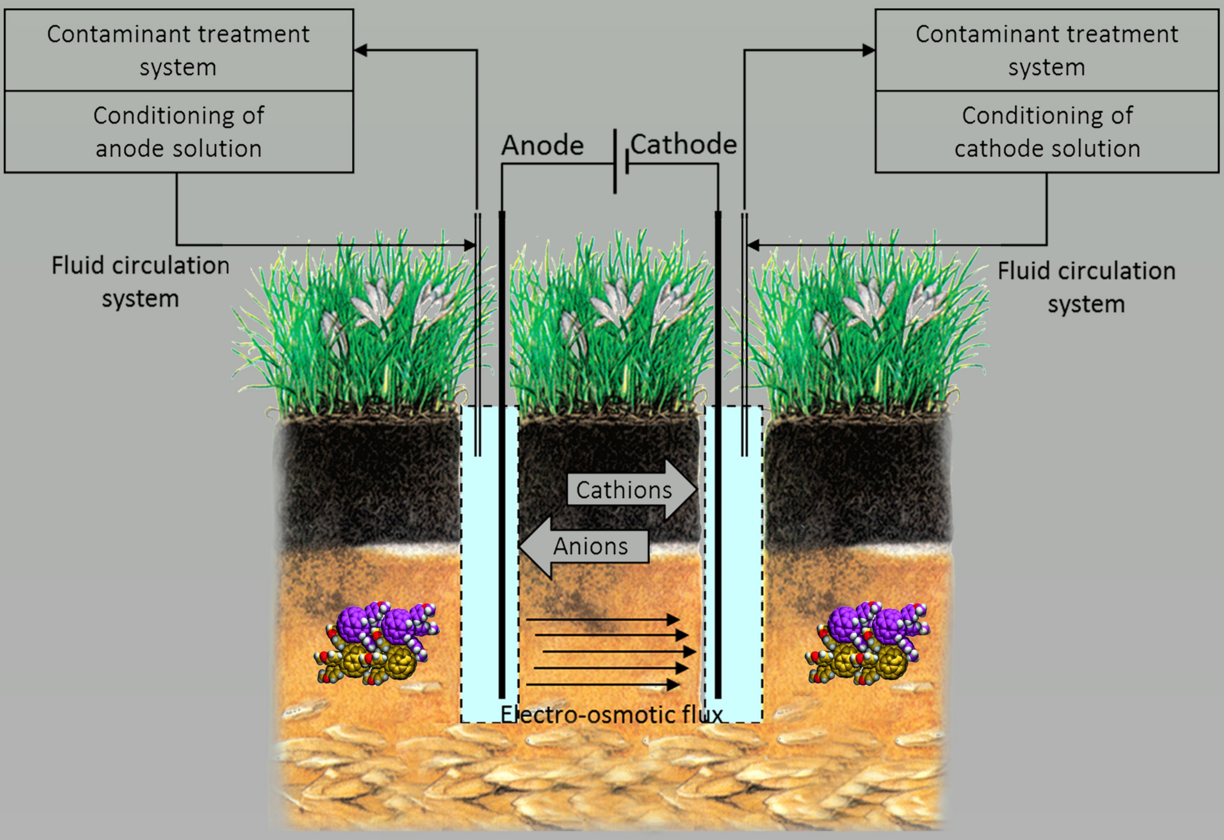
$$\boldsymbol{M^{n+} + OH^{-} + Y^{4-} \Leftrightarrow MY(OH)^{n-5}}$$

In natural clays, the use of EDTA thereby holds the potential to keep a large quantity of heavy metals in the solutions phase; thereby electrolytic migration will tend towards the anode, due to formation of negative metal EDTA complexes. This is an indication that EDTA increased the mobilization of nickel ions thereby making the metal accessible for electrolytic migration and electroosmosis. Since the stability of the Ni-EDTA complexes is high, it prevents their exchange onto the soil particles, effectively increasing their tendency to remain in the pore solution. This migration continues in response to the applied electrical gradient and continues till the precipitation of the complexes occurs. As compared to EDTA the efficiency of all other cathodic purging solutions was less, with Igepal CA 720 showing the lowest removal efficiency. The removal of nickel may not have occurred due to its possible precipitation as a hydroxide due to the high pH condition at the cathode section. In case with Tween 80 the removal is possibly a slight better due possibly due to the layer being rather small or thin close to the cathode. Similarly the use of $NaNO_3$, gives a lower removal efficiency, since the nitrate ions do not easily form a complex with the heavy metals under similar high pH conditions, whereas the formation always require extreme low pH condition which are difficult to form when using it with a combination of NaCl.

Looking at the complete discussion as presented in the chapter it can be proposed that the removal efficiency of any heavy metal for that matter of fact or a given combination of metals needs to be studied individually. The process as well as the combination of purging solutions for a given heavy metal and a given concentration is bound to vary or change in case there is change in the concentration or any other inorganic heavy metal or organic compound being present in the contaminated soil. Also application and energy consumption of the method need to be reviewed when the method is to be applied on the field, wherein the electrode spacing and configuration may be a lot different than the laboratory scale studies.

CHAPTER 4

ELECTROKINETIC GROUTING FOR PROBLEMATIC SOIL STABILIZATION



Electrokinetic Grouting for Problematic Soil Stabilization

Chapter Four

4.1 INTRODUCTION

Conventional soil stabilization or strengthening involve the addition of cementing materials such as lime or Portland cement. The primary objective being to produce a cementing phase such as calcium silicate hydrate, calcium carbonate or calcium sulphate. The choice of ground improvement techniques for soft soils is not only governed by direct costs, but also the long term maintenance costs, time duration for strength improvement, duration of completion and cost benefits. Therefore, conventional methods widely used to avoid or minimize this problem also include preloading the soft soil layer with surcharge and installing vertical drains to accelerate consolidation. In some cases, these methods are not suitable to stabilize soil with existing structures since it may require significant excavation or cause soil disturbance. Therefore, new methods are needed to stabilize soft soils with low hydraulic conductivities while minimizing ground disturbances. There are few options for stabilisation of fine grained under this circumstance such as soil freezing, hydrofracture grouting, and electroosmotic consolidation. All these methods have been shown to result in measurable ground movements that are potentially damaging to adjacent and overlying structures.

The electrokinetic stabilisation method has been shown a very excellent potential to remediate those deficiencies. It has been reported by many researchers that the electrokinetic stabilisation technique can be less expensive than other remedial techniques and has the added advantage of not disturbing site activities. Electrokinetic stabilisation can be considered a very new technique, technically innovative, and more cost effective than conventional methods of soil stabilisation using mix-in-place processes; but it is still not widely implemented on site. Even though there is evidence from previous studies in laboratory and case study that electrokinetic stabilisation has shown promising results for improving the strength of soft soils, it has not convinced enough engineers to use it more as an alternative method. Moreover, the complexity of electrochemical processes involved and long term issue caused by corrosion of electrodes has clearly become an obstacle for implementation of this method in the fields. Hopefully, by doing in depth study of electrokinetic stabilisation, this research will play a very important role in a future in order to promote a new and effective technique to improve problematic soils.

4.2 ELECTROKINETIC GROUTING

Electrokinetic stabilisation is a ground improvement method in which stabilizing agents are induced into soil under direct current. The movement of stabilizing agents into soil masses is governed by the principles of electrokinetics, while mechanisms of stabilization can be explained by the principles of chemical stabilisation. When cations are used as stabilizing agents, ions migrate into soils through processes of electromigration and electroosmosis. These ions improve the soil strength by three mechanisms, namely cation exchange, mineralization and precipitation of species in the pore fluid.

For the envisaged work of the research seven different types of soils were selected. All collected soils were air dried, pulverized and kept for 100^{o}C for 24 hours. Soil 3, Soil 2 and Soil 4 were then sieved through a 2 mm sieve prior to use whereas Soil 1, Soil 4 and Soil 6 were sieved through a 425 μ sieve prior to use and Soil 7 was used directly as it was a commercially available soil (Table 4.1). The various factors considered for study in the work included effect of soil composition; periodic supply; experimental duration; voltage gradient, size of reactor; anode concentration; reactant type and its concentration; low frequency AC supply; and grout concentration. These sets of experiments were carried out on open electrokinetic reactors with one face of the soil being exposed to the atmosphere. Another set of experiments were carried out in closed electrokinetic reactors to replicate deep seated soil grouting. This set included study of factors such as soil composition, grout concentration, experimental duration and electrode spacing. The following aspects were kept in mind and maintained with utmost care while performing experiments:

- All materials and chemicals were used as received.
- For all the procedures, only distilled water was used.
- Connection or joints of the reactor were sealed properly to avoid any leakage during the performance of experiments using chemicals that do not hinder or facilitate the performance of the test or the end results.

Table 4.1 Soil Code Name

Soil	Place of Procurement	Code Name
Black Cotton Soil	Netrang	Soil 1
Sandy Silt	Hajira	Soil 2
Black Sand	Valsad	Soil 3
Yellow Silty Soil	Vadodara	Soil 4
Sand	Bhadarpur	Soil 5
Yellow Soil	Sevasi	Soil 6
Kaolinite	Bhavnagar	Soil 7

4.3 AIMS

- **Remediation Using Electrokinetic Grouting**
  - The scope of the present investigation is to study the possibility of using electrokinetics as a technique to grout fine grained soils which under normal circumstances would require either higher pressure or some specialized technique to grout the soil mass, which in turn may disturb adjacent structures.
  - The research undertaken at present envisages the study of this technique in various kinds of soils and also to study the effect of grout concentration being used. The

parameters for the study included varying the concentration of grout, the type of fine grained soil to be improved, duration of the process, concentration and type of reactant i.e. hardener, applied voltage gradient, electrode spacing, periodic supply, low frequency AC supply and size of electrokinetic reactor. It has been proposed to use the process of electrokinetics as a tool to grout fine grained soils to increase the shearing strength of soft soils found at greater depths, remediation of which poses a great problem to geotechnical engineers, when encountered under existing structure. The efficiency of the method was evaluated with the use of strength and permeability measurements pre and post process as well as during the process. The grout flow in the soil mass was validated using scanning electron microscopy (SEM) & energy dispersive spectroscopy (EDS) to analyze the soil samples collected from different compartments of the electrokinetic reactor.

4. 4 EXPERIMENTAL DEVELOPMENT AND MEASUREMENTS

Experimental developments for the complete work for electrokinetic grouting were made in house. Electrokinetic grouting used both open and closed electrokinetic reactors for the experimentations, details for which have been elaborated below.

4.4.1 Electrokinetic Reactors

The material used for fabrication of the electrokinetic reactors was selected keeping in mind the process of electrokinetics for which reason, use of any type of metal was avoided as far as possible. Details of the fabrication and dimensions for the same are discussed below.

4.4.1.1 Open Reactors

Four laboratory scale reactors were prepared using 8 mm thick acrylic sheet as shown in the Fig 4.1, 4.2, 4.3 and 4.4. The detailed size of each of the reactor is given in Table 4.2. Each reactor has compartments for purging solutions & filter chambers. The bifurcating acrylic sheets of the compartments had perforation to allow flow to the grout in the soil. Filter papers were pasted on the acrylic sheets of the compartments to restrict intermixing of the filter media with the grout components or the test soil. Figure 4.5(a) & (b) shows the schematic diagram of the laboratory electrokinetic reactor and complete setup respectively.

4.4.1.2 Close Reactors

The closed reactors used are already discussed in Chapter 3 earlier.

Table 4.2 Dimensions of Open Reactors

Reactor No.	L cm	H cm	W cm	Fill Ht. cm	Volume cm^3
o/p 1	8.3	19.8	10.2	15	1269.9
o/p 2	18.2	19.5	15.5	15	4231.5
o/p 3	25	19.8	20	15	7500
o/p 4	41	22	30	15	18450

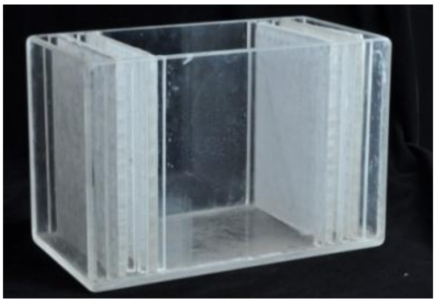


Fig 4.1 Open Reactor 1 (o/p 1)

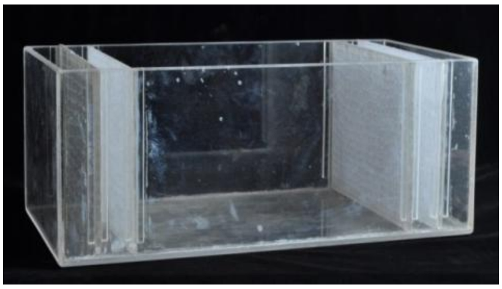


Fig 4.3 Open Reactor 3 (o/p 3)

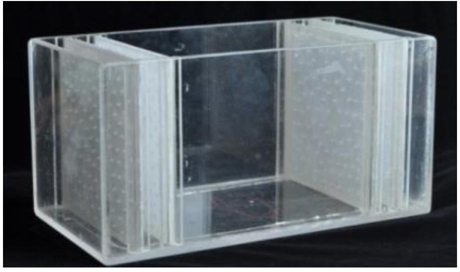


Fig 4.2 Open Reactor 2 (o/p 2)

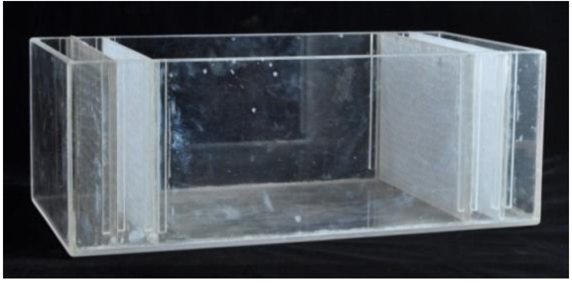


Fig 4.4 Open Reactor 4 (o/p 4)

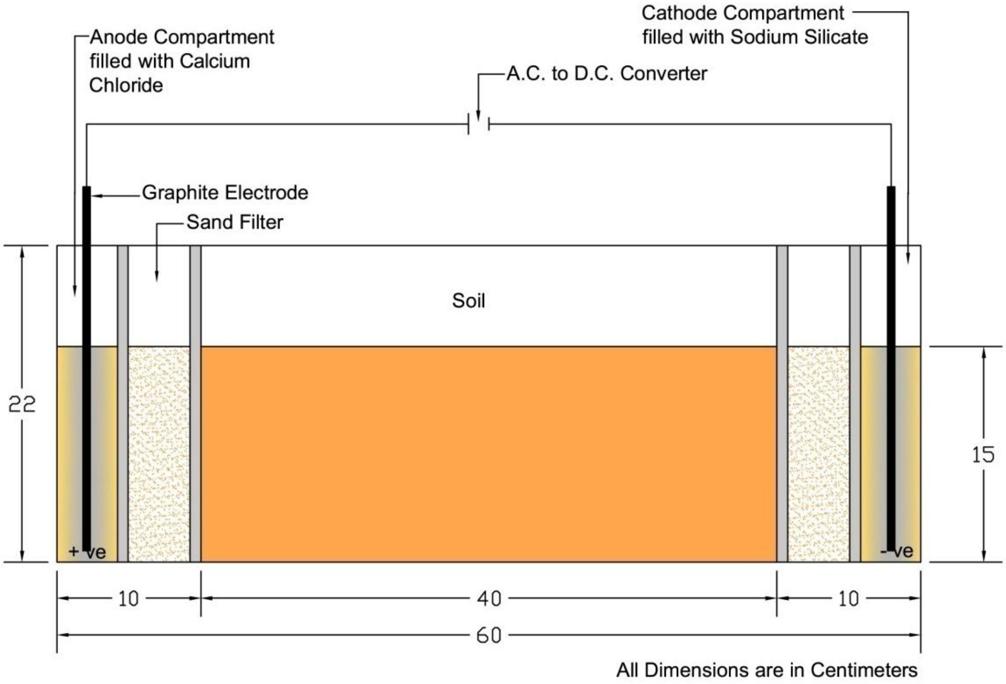


Fig. 4.5(a) Schematic Diagram of the Laboratory Reactor

4.4.2 Setup and Conduction of Experiments

To conduct the electrokinetic grouting experiment, soil mass was compacted in the open electrokinetic reactor by hand compaction. One 10 mm diameter and 30 cm long carbon electrode was placed in each of the compartments and connected to the AC-DC convertor unit. The solutions used in the cathode and anode compartments were allowed to flow into the soil section, react with each other, thereby producing a grouted mass. All cohesionless sands were compacted at 88% relative density and all other soils on the wet side of 88% of MDD. Duration of testing was 35 days for all the phases when using the open electrokinetic reactor and 10 days for the closed electrokinetic reactor except the experiments for the phase involving optimization of experimental duration.

4.4.3 Observations

For all the experiments, readings of current, voltage (near anode, mid section, near cathode), and ambient temperature were taken at a fixed interval of time on a daily basis.

Fig. 4.5(b) Complete Setup of Electrokinetic Procedure

4.4.4 Collection of Samples

For the Unconfined Compression Strength (UCS) Test, three PVC pipes of 20 cm length and 38 mm inside diameter (Fig. 4.6) were inserted into the soil near anode, at center and near cathode at the end of experiments, for UCS samples of the grouted soil for o/p3 and o/p4. For reactor o/p2 the samples were collected from near anode and cathode and for reactor o/p 1 from middle section. PVC pipes were used for collection of samples since PVC is bad conductor of electricity, thereby not affecting the grouting process. For close reactor the strength was measured near anode, at mid-length and near cathode by vane shear apparatus. In order to check for reduction in permeability of the grouted soil, three undisturbed samples were collected from near anode, at mid length and from near cathode, with the help of a 15 cm long and 28 mm inside diameter sampler tube at the end of each experiment for open reactor. Figure 4.7 shows the representation of sampler tube for open reactor and Figure 4.8 shows for the modification used for the closed reactor for permeability test after the electrokinetic grouting procedure was carried out. At the end of the experiment, soil samples were collected from the reactor from anode section, mid length and cathode section. The sample was then air dried and pulverized before being tested using EDAX to determine the percent sodium concentration.

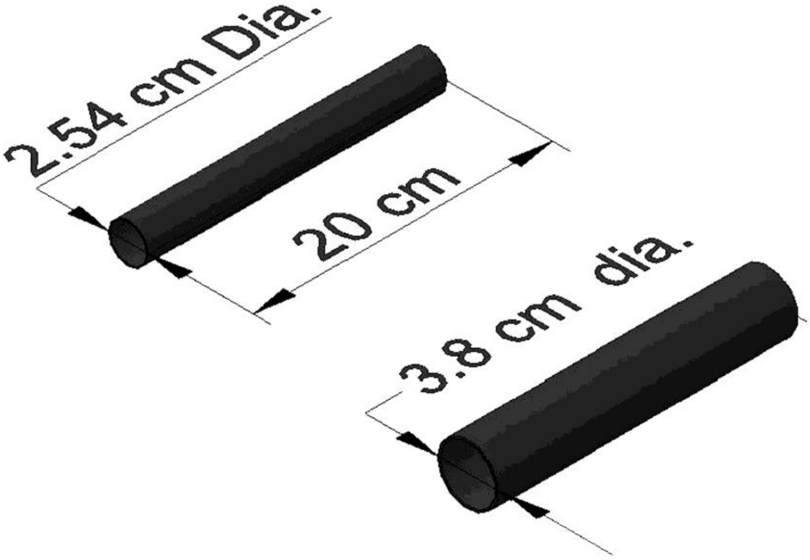


Fig. 4.6 PVC Pipe Sampler for UCS Sample (Open Reactor)

Fig. 4.7 Sampler Tube for Permeability (Open Reactor)

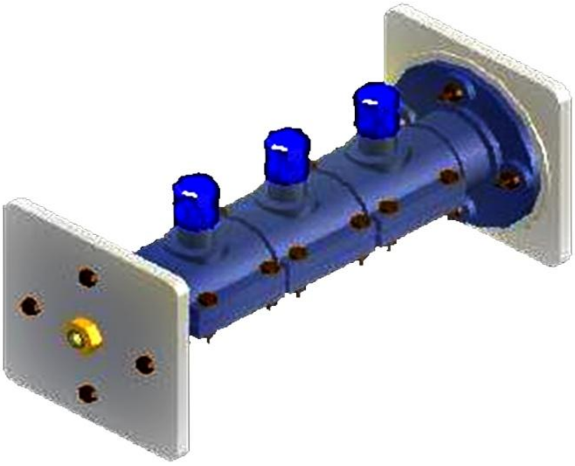


Fig. 4.8 Modification of Closed Reactor for Permeability Test

4.5 EXPERIMENTAL SCHEDULE

The complete work for electrokinetic grouting was carried out on open and closed electrokinetic reactors the details of which have been explained in the previous sections. The details of all experiments are tabulated in the tables with respect to the factor studied (Table 4.3 and Table 4.4). The codes used in these tables are described as below:

Letter	Description	Experimental Designation	Description
O	Open Reactor	OSC1	Open Reactor Soil Composition Soil 1
SC	Soil Composition	OED 2-1	Open Reactor Experimental Duration Soil 2 First Set
ED	Experimental Duration	OED 0.5 4-1	Open Reactor Experimental Duration Soil 4 First Set Voltage Applied Half of Standard 25V
PS	Periodic Supply	OPS 1/1	Open Reactor Periodic Supply 1 day ON/1 day OFF
AC	Anode Concentration	OAC 2-1	Open Reactor Anode Concentration Soil 2 First Set
RS	Reactor Size	OAC 15 4-1	Open Reactor Anode Concentration 15% Sodium Silicate Soil 4 First Set
RC	Reactant Concentration	ORS 1	Open Reactor Size 1
LAC	Low Frequency AC Supply	OVG 25 1-1	Open Reactor Voltage Gradient 25% Sodium Silicate Soil 1, First Set (12.5V)
GC	Grout Concentration	OVGOP 2 4-1	Open Reactor Voltage Gradient Reactor 2, Soil 4 First Set (12.5V)
C	Closed Reactor	ORC Ca 4-1	Open Reactor Reactant Type and Concentration, Calcium Chloride Soil 4, First set
ES	Electrode Spacing	OLAC 1	Open Reactor Low Frequency AC Supply (0.25Hz)
VG	Voltage Gradient	OGC 0.5 4-1	Open Reactor Grout Concentration, Voltage half of Standard (25V)

The first integer value encountered shows the soil which has been used in the study. In case of voltage gradient only the first number is a decimal followed by the ratio of applied voltage with respect to the standard applied voltage of 25 volts

4.6 EXPERIMENTAL RESULTS AND DISCUSSION

For the experiments pertaining to electrokinetic grouting seven types of soils were used. The geotechnical properties of the virgin soil were found out using standard methods prescribed in relevant IS codes (IS 2720), and are summarized below in Table 4.5. The soils in their virgin conditions were tested for their chemical characteristics such as pH and sodium content, given in Table 4.5.

Table 4.3 Experimental Details for Open Electrokinetic Reactor

Phase	Effect	Experiment Designation	Soil	Type of Supply	Voltage	AC Frequency	Reactor No.	Cathode Solution	Anode Solution	No. of Days
1	Soil Composition	OSC1	Soil 1	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OSC2	Soil 2	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OSC3	Soil 3	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OSC4	Soil 4	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OSC5	Soil 5	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OSC6	Soil 6	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35
2	Experimental Duration	OED 2-1	Soil 2	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OED 2-2	Soil 2	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	42
		OED 2-3	Soil 2	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	49
		OED 2-4	Soil 2	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	56
		OED 2-5	Soil 2	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	63
		OED 2-6	Soil 2	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	70
		OED 4-1	Soil 4	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OED 4-2	Soil 4	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	42
		OED 4-3	Soil 4	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	49
		OED 4-4	Soil 4	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	56
		OED 4-5	Soil 4	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	63
		OED 4-6	Soil 4	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	70
		OED 4-7	Soil 4	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	77
		OED 0.5 4-1	Soil 4	DC	12.5	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OED 0.5 4-2	Soil 4	DC	12.5	Nil	o/p 4	25% SS	2% $CaCl_2$	42
		OED 0.5 4-3	Soil 4	DC	12.5	Nil	o/p 4	25% SS	2% $CaCl_2$	56
		OED 0.5 4-4	Soil 4	DC	12.5	Nil	o/p 4	25% SS	2% $CaCl_2$	63
		OED 0.5 4-5	Soil 4	DC	12.5	Nil	o/p 4	25% SS	2% $CaCl_2$	70
		OED 0.5 4-6	Soil 4	DC	12.5	Nil	o/p 4	25% SS	2% $CaCl_2$	77

Table 4.3 Experimental Details for Open Electrokinetic Reactor (Cont'd)

Phase	Effect	Experiment Designation	Soil	Type of Supply	Voltage	AC Frequency	Reactor No.	Cathode Solution	Anode Solution	No. of Days
3	Periodic Supply	OPS 1/1	Soil 4	DC	5	Nil	o/p 1	25% SS	2% $CaCl_2$	35
		OPS C	Soil 4	DC	5	Nil	o/p 1	25% SS	2% $CaCl_2$	35
		OPS 2/1	Soil 4	DC	5	Nil	o/p 1	25% SS	2% $CaCl_2$	35
		OPS 1/2	Soil 4	DC	5	Nil	o/p 1	25% SS	2% $CaCl_2$	35
4	Anode Concentration	OAC 2-1	Soil 2	DC	25	Nil	o/p 4	25% SS	1% $CaCl_2$	35
		OAC 2-2	Soil 2	DC	25	Nil	o/p 4	25% SS	1.5% $CaCl_2$	35
		OAC 2-3	Soil 2	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OAC 2-4	Soil 2	DC	25	Nil	o/p 4	25% SS	2.5% $CaCl_2$	35
		OAC 15 4-1	Soil 4	DC	25	Nil	o/p 4	15% SS	1% $CaCl_2$	35
		OAC 15 4-2	Soil 4	DC	25	Nil	o/p 4	15% SS	1.5% $CaCl_2$	35
		OAC 15 4-3	Soil 4	DC	25	Nil	o/p 4	15% SS	2% $CaCl_2$	35
		OAC 15 4-4	Soil 4	DC	25	Nil	o/p 4	15% SS	2.5% $CaCl_2$	35
		OAC 20 4-1	Soil 4	DC	25	Nil	o/p 4	20% SS	1% $CaCl_2$	35
		OAC 20 4-2	Soil 4	DC	25	Nil	o/p 4	20% SS	1.5% $CaCl_2$	35
		OAC 20 4-3	Soil 4	DC	25	Nil	o/p 4	20% SS	2% $CaCl_2$	35
		OAC 20 4-4	Soil 4	DC	25	Nil	o/p 4	20% SS	2.5% $CaCl_2$	35
		OAC 25 4-1	Soil 4	DC	25	Nil	o/p 4	25% SS	1% $CaCl_2$	35
		OAC 25 4-2	Soil 4	DC	25	Nil	o/p 4	25% SS	1.5% $CaCl_2$	35
		OAC 25 4-3	Soil 4	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OAC 25 4-4	Soil 4	DC	25	Nil	o/p 4	25% SS	2.5% $CaCl_2$	35
5	Reactor Size	ORS 1	Soil 4	DC	5	Nil	o/p 1	25% SS	2% $CaCl_2$	35
		ORS 2	Soil 4	DC	10.9	Nil	o/p 2	25% SS	2% $CaCl_2$	35
		ORS 3	Soil 4	DC	15	Nil	o/p 3	25% SS	2% $CaCl_2$	35
		ORS 4	Soil 4	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35

Table 4.3 Experimental Details for Open Electrokinetic Reactor (Cont'd)

Phase	Effect	Experiment Designation	Soil	Type of Supply	Voltage	AC Frequency	Reactor No.	Cathode Solution	Anode Solution	No. of Days
6	Voltage Gradient	OVG 25 1-1	Soil 1	DC	12.5	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OVG 25 1-2	Soil 1	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OVG 25 2-1	Soil 2	DC	12.5	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OVG 25 2-2	Soil 2	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OVG 25 3-1	Soil 3	DC	12.5	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OVG 25 3-2	Soil 3	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OVG 15 4-1	Soil 4	DC	12.5	Nil	o/p 4	15% SS	2% $CaCl_2$	35
		OVG 15 4-2	Soil 4	DC	25	Nil	o/p 4	15% SS	2% $CaCl_2$	35
		OVG 15 4-3	Soil 4	DC	37.5	Nil	o/p 4	15% SS	2% $CaCl_2$	35
		OVG 20 4-1	Soil 4	DC	12.5	Nil	o/p 4	20% SS	2% $CaCl_2$	35
		OVG 20 4-2	Soil 4	DC	25	Nil	o/p 4	20% SS	2% $CaCl_2$	35
		OVG 20 4-3	Soil 4	DC	37.5	Nil	o/p 4	20% SS	2% $CaCl_2$	35
		OVG 25 4-1	Soil 4	DC	12.5	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OVG 25 4-2	Soil 4	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OVG 25 4-3	Soil 4	DC	37.5	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OVG 30 4-1	Soil 4	DC	12.5	Nil	o/p 4	30% SS	2% $CaCl_2$	35
		OVG 30 4-2	Soil 4	DC	25	Nil	o/p 4	30% SS	2% $CaCl_2$	35
		OVG 30 4-3	Soil 4	DC	37.5	Nil	o/p 4	30% SS	2% $CaCl_2$	35
		OVGOP 2 4-1	Soil 4	DC	10.9	Nil	o/p 2	25% SS	2% $CaCl_2$	35
		OVGOP 2 4-2	Soil 4	DC	13.7	Nil	o/p 2	25% SS	2% $CaCl_2$	35
		OVGOP 2 4-3	Soil 4	DC	18.2	Nil	o/p 2	25% SS	2% $CaCl_2$	35
		OVGOP 2 4-4	Soil 4	DC	22.8	Nil	o/p 2	25% SS	2% $CaCl_2$	35
		OVGOP 2 4-5	Soil 4	DC	27.3	Nil	o/p 2	25% SS	2% $CaCl_2$	35

Table 4.3 Experimental Details for Open Electrokinetic Reactor (Cont'd)

Phase	Effect	Experiment Designation	Soil	Type of Supply	Voltage	AC Frequency	Reactor No.	Cathode Solution	Anode Solution	No. of Days
7	Reactant Type and Concentration	ORC Ca 4-1	Soil 4	DC	5	Nil	o/p 1	20% SS	2% $CaCl_2$	35
		ORC Ca 4-2	Soil 4	DC	5	Nil	o/p 1	20% SS	2.5% $CaCl_2$	35
		ORC Ca 4-3	Soil 4	DC	5	Nil	o/p 1	20% SS	3% $CaCl_2$	35
		ORC Na 4-1	Soil 4	DC	5	Nil	o/p 1	20% SS	2% $NaHCO_3$	35
		ORC Na 4-2	Soil 4	DC	5	Nil	o/p 1	20% SS	2.5% $NaHCO_3$	35
		ORC Na 4-3	Soil 4	DC	5	Nil	o/p 1	20% SS	3% $NaHCO_3$	35
		ORC Al 4-1	Soil 4	DC	5	Nil	o/p 1	20% SS	2% $Al_2(SO_4)_3.16H_2O$	35
		ORC Al 4-2	Soil 4	DC	5	Nil	o/p 1	20% SS	2.5% $Al_2(SO_4)_3.16H_2O$	35
		ORC Al 4-3	Soil 4	DC	5	Nil	o/p 1	20% SS	3% $Al_2(SO_4)_3.16H_2O$	35
8	Low Frequency A/C Supply	OLAC 1	Soil 4	AC	5	0.25 Hz	o/p 1	25% SS	2% $CaCl_2$	35
		OLAC 2	Soil 4	AC	5	0.5 Hz	o/p 1	25% SS	2% $CaCl_2$	35
		OLAC 3	Soil 4	AC	5	0.75 Hz	o/p 1	25% SS	2% $CaCl_2$	35
		OLAC 4	Soil 4	AC	5	1 Hz	o/p 1	25% SS	2% $CaCl_2$	35
9	Grout Concentration	OGC 0.5 4-1	Soil 4	DC	12.5	Nil	o/p 4	15% SS	2% $CaCl_2$	35
		OGC 0.5 4-2	Soil 4	DC	12.5	Nil	o/p 4	20% SS	2% $CaCl_2$	35
		OGC 0.5 4-3	Soil 4	DC	12.5	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OGC 0.5 4-4	Soil 4	DC	12.5	Nil	o/p 4	30% SS	2% $CaCl_2$	35
		OGC 1 4-1	Soil 4	DC	25	Nil	o/p 4	15% SS	2% $CaCl_2$	35
		OGC 1 4-2	Soil 4	DC	25	Nil	o/p 4	20% SS	2% $CaCl_2$	35
		OGC 1 4-3	Soil 4	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OGC 1 4-4	Soil 4	DC	25	Nil	o/p 4	30% SS	2% $CaCl_2$	35
		OGC 1.5 4-1	Soil 4	DC	37.5	Nil	o/p 4	15% SS	2% $CaCl_2$	35
		OGC 1.5 4-2	Soil 4	DC	37.5	Nil	o/p 4	20% SS	2% $CaCl_2$	35
		OGC 1.5 4-3	Soil 4	DC	37.5	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OGC 1.5 4-3	Soil 4	DC	37.5	Nil	o/p 4	30% SS	2% $CaCl_2$	35

Table 4.3 Experimental Details for Open Electrokinetic Reactor (Cont'd)

Phase	Effect	Experiment Designation	Soil	Type of Supply	Voltage	AC Frequency	Reactor No.	Cathode Solution	Anode Solution	No. of Days
9	Grout Concentration	OGC 1 1-1	Soil 1	DC	25	Nil	o/p 4	15% SS	2% $CaCl_2$	35
		OGC 1 1-2	Soil 1	DC	25	Nil	o/p 4	20% SS	2% $CaCl_2$	35
		OGC 1 1-3	Soil 1	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OGC 1 1-4	Soil 1	DC	25	Nil	o/p 4	30% SS	2% $CaCl_2$	35
		OGC 0.5 1-1	Soil 1	DC	12.5	Nil	o/p 4	15% SS	2% $CaCl_2$	35
		OGC 0.5 1-2	Soil 1	DC	12.5	Nil	o/p 4	20% SS	2% $CaCl_2$	35
		OGC 0.5 1-3	Soil 1	DC	12.5	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OGC 0.5 1-4	Soil 1	DC	12.5	Nil	o/p 4	30% SS	2% $CaCl_2$	35
		OGC 1 2-1	Soil 2	DC	25	Nil	o/p 4	15% SS	2% $CaCl_2$	35
		OGC 1 2-2	Soil 2	DC	25	Nil	o/p 4	20% SS	2% $CaCl_2$	35
		OGC 1 2-3	Soil 2	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OGC 1 2-4	Soil 2	DC	25	Nil	o/p 4	30% SS	2% $CaCl_2$	35
		OGC 0.5 2-1	Soil 2	DC	12.5	Nil	o/p 4	15% SS	2% $CaCl_2$	35
		OGC 0.5 2-2	Soil 2	DC	12.5	Nil	o/p 4	20% SS	2% $CaCl_2$	35
		OGC 0.5 2-3	Soil 2	DC	12.5	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OGC 0.5 2-4	Soil 2	DC	12.5	Nil	o/p 4	30% SS	2% $CaCl_2$	35
		OGC 1 3-1	Soil 3	DC	25	Nil	o/p 4	15% SS	2% $CaCl_2$	35
		OGC 1 3-2	Soil 3	DC	25	Nil	o/p 4	20% SS	2% $CaCl_2$	35
		OGC 1 3-3	Soil 3	DC	25	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OGC 1 3-4	Soil 3	DC	25	Nil	o/p 4	30% SS	2% $CaCl_2$	35
		OGC 0.5 3-1	Soil 3	DC	12.5	Nil	o/p 4	15% SS	2% $CaCl_2$	35
		OGC 0.5 3-2	Soil 3	DC	12.5	Nil	o/p 4	20% SS	2% $CaCl_2$	35
		OGC 0.5 3-3	Soil 3	DC	12.5	Nil	o/p 4	25% SS	2% $CaCl_2$	35
		OGC 0.5 3-4	Soil 3	DC	12.5	Nil	o/p 4	30% SS	2% $CaCl_2$	35

Table 4.4 Experimental Detail for Closed Electrokinetic Reactor

Phase	Effect	Experiment Designation	Soil	Type of Supply	Voltage	Reactor No.	Cathode Solution	Anode Solution	No of Days
1	Soil Composition	CSC1	Soil 1	DC	20.7	c/m 1	25% SS	2% $CaCl_2$	10
		CSC2	Soil 2	DC	20.7	c/m 1	25% SS	2% $CaCl_2$	10
		CSC3	Soil 4	DC	20.7	c/m 1	25% SS	2% $CaCl_2$	10
		CSC4	Soil 5	DC	20.7	c/m 1	25% SS	2% $CaCl_2$	10
		CSC5	Soil 6	DC	20.7	c/m 1	25% SS	2% $CaCl_2$	10
		CSC5	Soil 7	DC	20.7	c/m 1	25% SS	2% $CaCl_2$	10
2	Grout Concentration	CGC1	Soil 5	DC	20.7	c/m 1	20% SS	2% $CaCl_2$	10
		CGC2=CSC4	Soil 5	DC	20.7	c/m 1	25% SS	2% $CaCl_2$	10
		CGC3	Soil 5	DC	20.7	c/m 1	30% SS	2% $CaCl_2$	10
3	Experimental Duration	CED1=CSC5	Soil 6	DC	20.7	c/m 1	25% SS	2% $CaCl_2$	10
		CED2	Soil 6	DC	20.7	c/m 1	25% SS	2% $CaCl_2$	20
		CED3	Soil 6	DC	20.7	c/m 1	25% SS	2% $CaCl_2$	25
		CED4	Soil 6	DC	20.7	c/m 1	25% SS	2% $CaCl_2$	30
		CED5	Soil 6	DC	20.7	c/m 1	25% SS	2% $CaCl_2$	35
4	Electrode Spacing	CES1=CSC4	Soil 6	DC	20.7	c/m 1	25% SS	2% $CaCl_2$	10
		CES2	Soil 6	DC	27.4	c/m 2	25% SS	2% $CaCl_2$	10
		CES3	Soil 6	DC	41.1	c/m 3	25% SS	2% $CaCl_2$	10
		CES4	Soil 6	DC	54.9	c/m 4	25% SS	2% $CaCl_2$	10

Experimental Designation	Description	Experimental Designation	Description
CSC 1	Closed Reactor Soil Composition First Set	CED1	Closed Reactor Experimental Duration First Set
CGC 1	Closed Reactor Grout Concentration 20% Sodium Silicate	CES1	Closed Reactor Electrode Spacing First Set

Table 4.5 Properties of Soils for Electrokinetic Grouting

Property	Black Cotton Soil	Silty Sand	Black Sand	Yellow Silty Soil	Sand	Yellow Soil	Kaolinite
Place of Procurement	Netrang	Hazira	Dahej	Vadodara	Bhadarpur	Sevasi	Commercial
Code Name	Soil 1	Soil 2	Soil 3	Soil 4	Soil 5	Soil 6	Soil 7
M.D.D (gm/cc)	1.65	–	–	1.76	–	1.72	1.38
O.M.C (%)	19.2	–	–	13.8	–	17.3	32.3
Liquid limit (%)	54	–	–	30	–	32	73.8
Plastic limit (%)	25	–	–	NP	–	20	33.2
e_{max}	–	0.595	0.796	–	0.895	–	–
e_{min}	–	0.438	0.492	–	0.534	–	–
D_{10} (mm)	–	0.240	0.168	–	0.140	–	–
Coefficient of Uniformity (Cu)	–	2.500	3.287	–	3.428	–	–
Coefficient of Curvature (Cc)	–	1.17	1.09	–	1.08	–	–
Plastic limit (%)	–	NP	NP	–	NP	–	–
IS Classification	CH	SW	SW	ML	SW	CL	CH
UCS (kg/cm^2)	3.51	–	–	0.68	–	2.44	2.87
Angle of Internal Friction	–	28.19	34.76	–	36.61	–	–
Specific Gravity	2.64	2.92	2.72	2.56	2.73	2.66	2.3
Free Swell (%)	70	NS	NS	33.33	NS	50	96
Coefficient of Permeability (cm/s)	5.32E-06	1.98E-02	1.94E-02	1.38E-06	4.67E-03	6.12E-06	7.2E-07
pH	7.07	7.92	8.2	7.09	7.71	7.51	8.2
Sodium (mg/kg)	53.2	53.9	54	41.3	32.9	42	14.7

4.6.1 Open Reactor

4.6.1.1 Effect of Soil Composition

Analysis: Figure 4.9 show the comparative plot of percentage permeability decrease for all the soils, post treatment. The maximum decrease in the permeability was observed in Soil 2 which decreased by 81% where approximately no change in permeability value was observed in case of Soil 1. The decrease observed in Soil 3 was 57%, Soil 4 was 72%, Soil 5 was 61% and Soil 6 was 75%. The maximum increase in the UCS was observed in case of Soil 4 showing as increase of 204%. The minimum change in UCS was observed in Soil 6 (Table 4.6), with a marginal increase of 28.5%.

Discussion: The net increase in UCS observed in case of coarser soil (Soil 2, 3 and 5) is average much greater than that observed in case of fine grained clayey soil (Soil 1 and 6) which may be due to stronger gelation of reactants leading to the better bonding of the soil particles with the gel of the grout. Both these observations may be attributed to the nature of the soil. Electrokinetic grouting results from the reaction between the reactants from the anode and the cathode which will flow faster towards each other in coarse soil as compared to fine grained clayey soil, thereby increasing the rate of reaction, which is directly reflected in the sodium content.

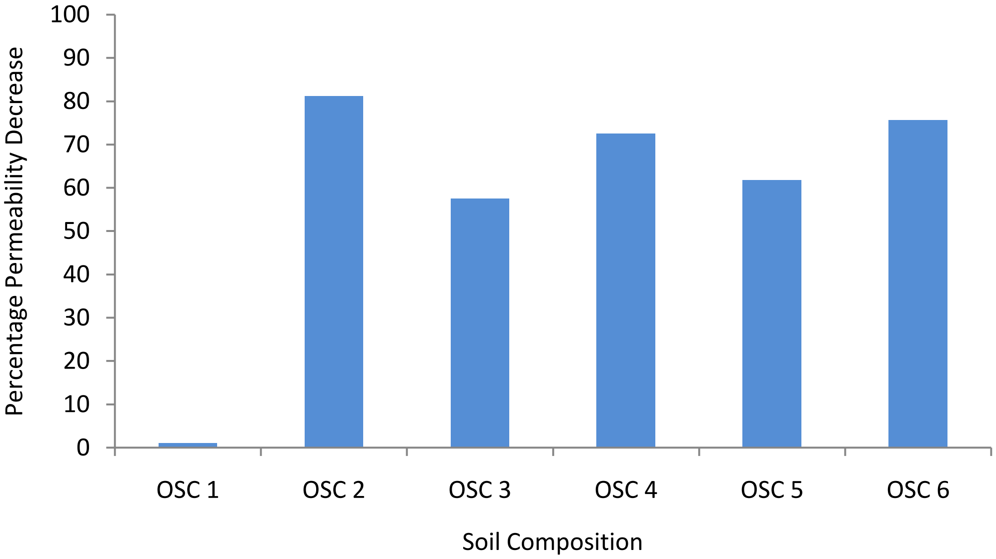


Fig. 4.9 Comparison of Permeability – Effect of Soil Composition

4.6.1.2 Effect of Experimental Duration

Analysis: Figure 4.10, 4.11 and 4.12 shows the comparative plot of percentage permeability decrease for Soil 2 and Soil 4, post treatment for various experimental durations. The improvement of permeability value increased with increase in the experimental duration upto 56 days beyond that the increase observed was not considerable. In the case when the voltage gradient was reduced for Soil 4 the overall percentage decrease in the permeability was much higher.

Table 4.6 Effect of Soil Composition on UCS and Permeability (Post Process)

Experiment Designation	OSC 1	OSC 2	OSC 3	OSC 4	OSC 5	OSC 6
$UCS_{postprocess}$ (kg/cm^2)	5.464	1.094	1.133	2.056	1.603	3.132
$k_{initial}$ (cm/sec)	5.32E-06	1.98E-02	1.94E-02	1.38E-06	5.32E-03	5.32E-06
k_{final} (cm/sec)	5.27E-06	3.73E-03	8.24E-03	3.79E-07	1.79E-03	1.50E-06

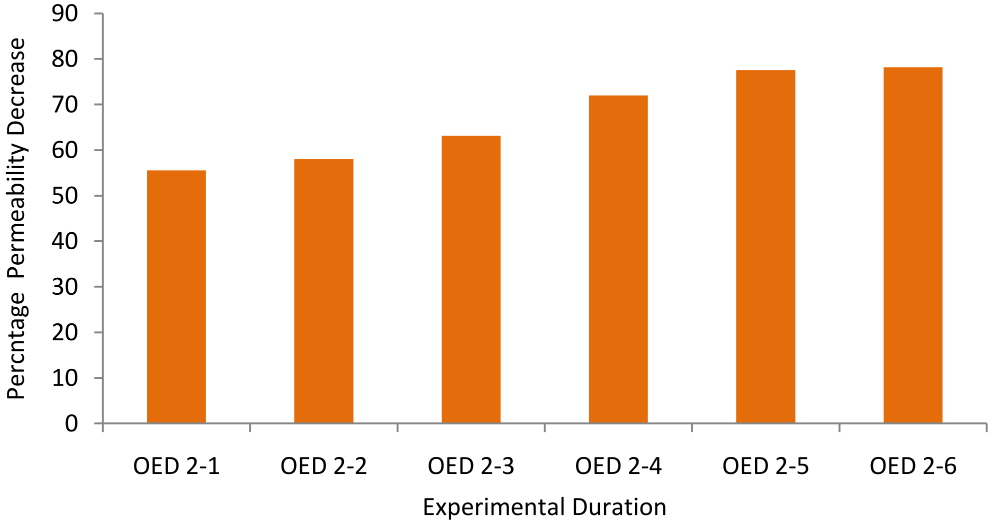


Fig. 4.10 Comparison of Permeability – Effect of Experimental Duration (Soil 2)

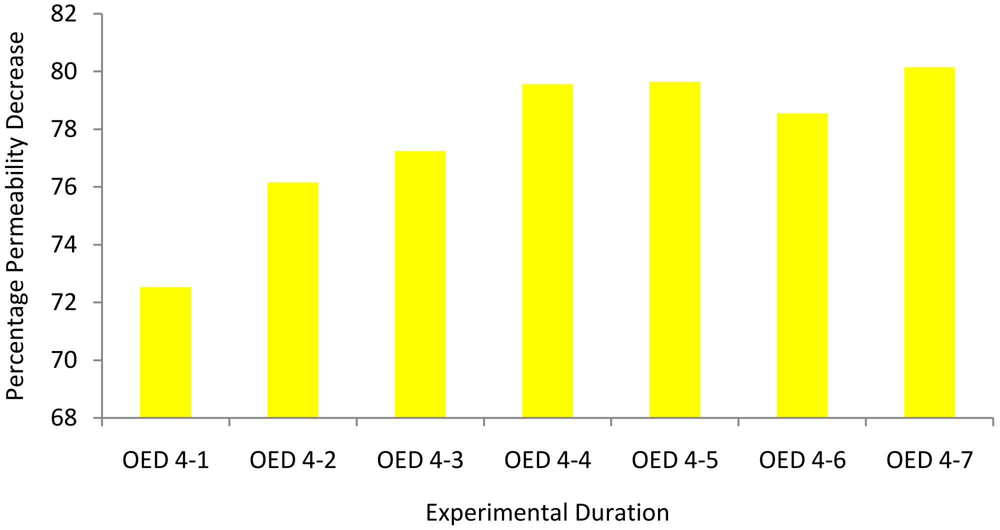


Fig. 4.11 Comparison of Permeability – Effect of Experimental Duration (Soil 4)

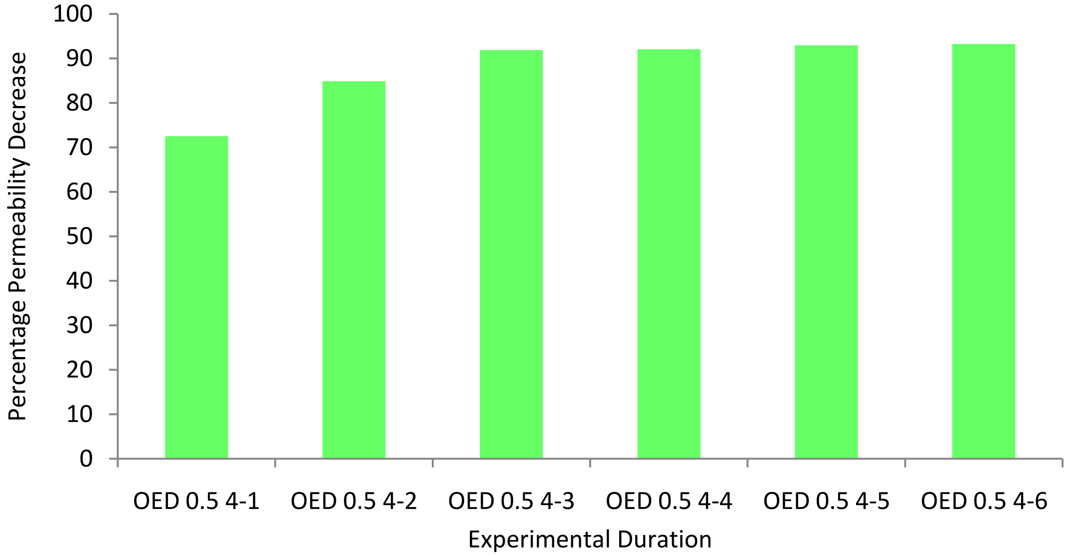


Fig. 4.12 Comparison of Permeability – Effect of Experimental Duration (Soil 4)
Applied Voltage = 12.5V

The increase in the UCS (Table 4.7, 4.8 and 4.9) was observed with increase in experimental duration as observed with permeability. The trend of observed for permeability in not observed in case of UCS with reducing voltage gradient. The increase in the UCS in case of reducing the voltage gradient shows no much different as with higher voltage gradient. This shows that in some cases the decrease in voltage gradient is beneficial for the soil. This observation may be attributed to the particular soil i.e. Soil 4 (ML), and may not hold good for other soils due to change in the nature of soil. Increase in UCS value with respect to Soil 2 has a maximum value of 1.183kg/cm^2 whereas the same increase for Soil 4 has a maximum value of 2.168kg/cm^2.

Table 4.7 Effect of Experimental Duration on UCS and Permeability (Post Process-Soil 2)

Experiment Designation	OED 2-1	OED 2-2	OED 2-3	OED 2-4	OED 2-5	OED 2-6
$UCS_{postprocess}$ (kg/cm^2)	0.895	0.912	0.970	1.067	1.168	1.183
$k_{initial}$ (cm/sec)	1.98E-02	1.98E-02	1.98E-02	1.98E-02	1.98E-02	1.98E-02
k_{final} (cm/sec)	8.80E-03	8.32E-03	7.30E-03	5.54E-03	4.45E-03	4.32E-03

Discussion: The increase in the duration gives a larger time for the completion of hydrolysis and gel formation from the already formed flocs. In case of Soil 2 (SW), the voids are larger in size which give the gel a possibility to shrink, another reason attributed to the lower increase in the UCS for sandy soil is the higher water content of the solution may be disadvantageous for forming a layer around the sand particles, preventing the gel to form a bond with each particle. In case of Soil 4 (ML), the soil particles are finer thereby forming much smaller voids which proves to be disadvantageous for the flow of the grout but the application of DC current causes the grout flow which improves the UCS, this is apparent from the smaller increase in the UCS values with increase in experimental duration. When the sample is subjected to long term treatment, the relatively larger OH^- ions still move slowly toward the anode, compared with the relatively smaller H^+ ions. During the movement of ions, the H^+ may react with the OH^- ions leading to the formation of H_2O, or it may react with Ca^{2+} ions and lead to the formation of $Ca(OH)_2$ as a precipitate which will neutralize the acidic front formed during the short term treatment. After neutralization, the alkaline front would have formed slowly and the pH would increase gradually from cathode to the anode, causing the alkaline region to increase. On the other hand, for high pH long term treatment, and high concentration of Ca^{2+}, the formation of a pozzolanic reaction is promoted, i.e. the formation of calcium – silicate – hydrate gel (CSH) under alkaline conditions. Significant increases are observed in the strength with increasing concentration of Ca^{2+} and pH.

Table 4.8 Effect of Experimental Duration on UCS and Permeability (Post Process-Soil 4)

Experiment Designation	$UCS_{postprocess}$ (kg/cm^2)	$k_{initial}$ (cm/sec)	k_{final} (cm/sec)
OED 4-1	2.056	1.38E-06	3.79E-07
OED 4-2	2.064	1.38E-06	3.29E-07
OED 4-3	2.069	1.38E-06	3.14E-07
OED 4-4	2.078	1.38E-06	2.83E-07
OED 4-5	2.097	1.38E-06	2.81E-07
OED 4-6	2.158	1.38E-06	2.96E-07
OED 4-7	2.168	1.38E-06	2.74E-07

Table 4.9 Effect of Experimental Duration on UCS and Permeability (Post Process- Soil 4) Applied Voltage = 12.5V

Experiment Designation	$UCS_{postprocess}$ (kg/cm^2)	$k_{initial}$ (cm/sec)	k_{final} (cm/sec)
OED 0.5 4-1	1.611	1.38E-06	3.79E-07
OED 0.5 4-2	2.009	1.38E-06	2.08E-07
OED 0.5 4-3	2.023	1.38E-06	1.12E-07
OED 0.5 4-4	2.055	1.38E-06	1.09E-07
OED 0.5 4-5	2.078	1.38E-06	9.70E-08
OED 0.5 4-6	2.104	1.38E-06	9.30E-08

4.6.1.3 Effect of Periodic Supply

Analysis: The study in this phase was carried out in order to reduce the energy consumption for the procedure. For this case, the DC supply was given intermittently varying the "ON" period and "OFF" period and comparing the results with the standard experiment wherein the supply was given continuously. Figure 4.13 shows the % permeability decrease for this phase, as it is seen there is some decrease when compared to the experiment with continuous supply in case of improvement of permeability. Improvement of the UCS (Table 4.10) value also follows the same trend.

Discussion: The decrease in improvement may be attributed to the reversal/obstruction of movement of charged ions and hindrance in the hydrolysis of water when the supply is switched OFF. The potential again needs some time to establish when the supply is powered ON again.

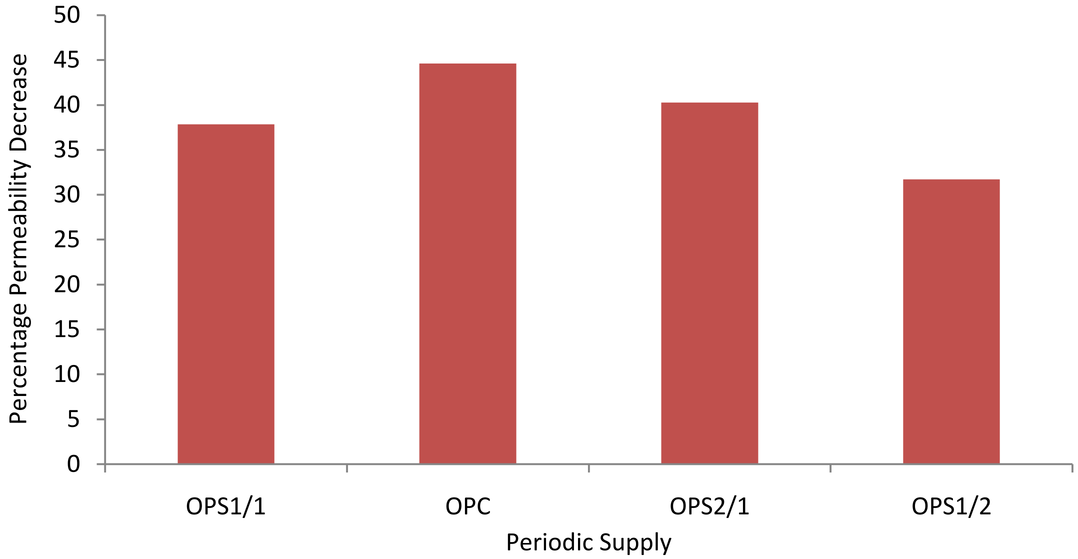


Fig. 4.13 Comparison of Permeability – Effect of Periodic Supply

Table 4.10 Effect of Periodic Supply on UCS and Permeability (Post Process)

Experiment Designation	OPS1/1	OPC	OPS2/1	OPS1/2
$UCS_{postprocess}$ (kg/cm^2)	1.157	1.545	1.304	1.046
$k_{initial}$ (cm/sec)	1.38E-06	1.38E-06	1.38E-06	1.38E-06
k_{final} (cm/sec)	8.58E-07	7.64E-07	8.24E-07	9.42E-07

4.6.1.4 Effect of Anode Concentration

Analysis: Figures 4.14, 4.15 and 4.16 shows the percentage of permeability for varying anode concentrations with change in the concentration of the cathode solution. The permeability decrease showed an improvement with increase in the concentration of the anode solution. For Soil 4, the decrease in the permeability is relatively higher as compared to Soil 2. The electrokinetic mobility increases with increase in concentration of $CaCl_2$. Tables 4.11 and 4.12 show the UCS values post treatment for Soil 2 and Soil 4 showing some increase in the UCS strength, though not very substantial. For Soil 4 it can be observed that the value of UCS varies from 0.84 kg/cm^2 to 1.54 kg/cm^2 for 15% sodium silicate grout, the same increase to 0.868 kg/cm^2 to 1.64 kg/cm^2 for 20% sodium silicate grout and for 25% sodium silicate grout, the increase varies from 1.02 kg/cm^2 to 2.08 kg/cm^2.

Discussion: The improvement in the UCS may be due to two reasons principally: contribution of pure electro-osmosis and contribution of the injection with grout. Improvement of undrained shear strength can be effectively extended or increased from the anode to the cathode by increasing experimental duration or treatment time for field problems. The mechanism of the electro-osmotic improvement without injection of grout solutions is primarily due to the attraction of the cations by the cathode. Thus, water moves towards the cathode with the cations and also due to by the electric potential. Injection of sodium silicate with calcium chloride as a reactant salt, leads to coagulation of the soil particles, and the undrained shear strength increases (Fig. 4.16). According to the Gouy–Chapman theory of the diffuse double layer, the diffuse double layer decreases in thickness with increasing salt content. With salt addition, the electrokinetic mobility of the ions decreases and the diffuse double layer is compressed. The diffuse double resulting in a decrease in the repulsive force between the clay mineral particles. The in turn allows the grout to flow easily resulting in a better grouted soil mass. At such small distances, hydration of the exchange cations and the clay mineral surface are the dominant driving forces for the gel formation to occur.

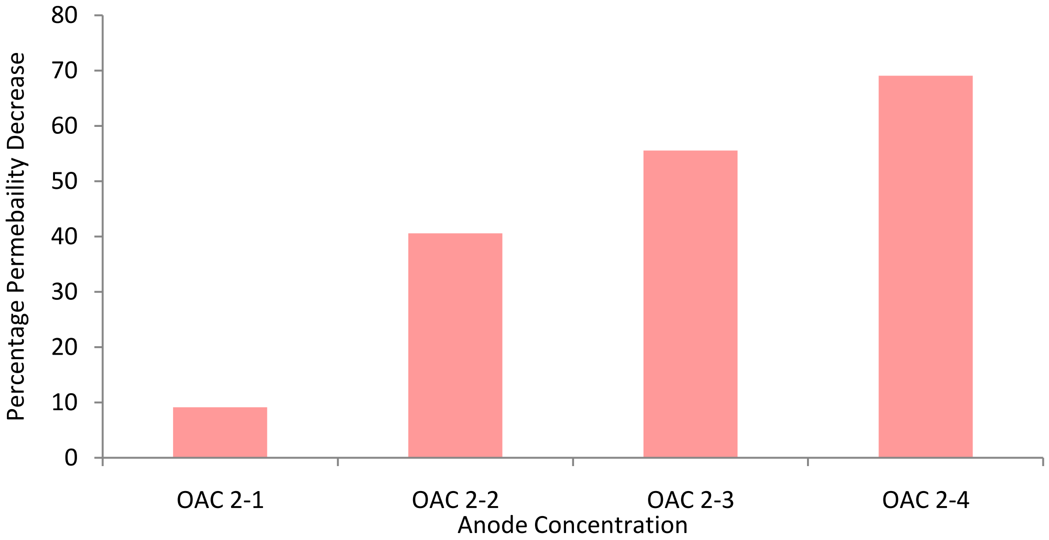


Fig. 4.14 Comparison of Permeability – Effect of Anode Concentration (Soil 2)

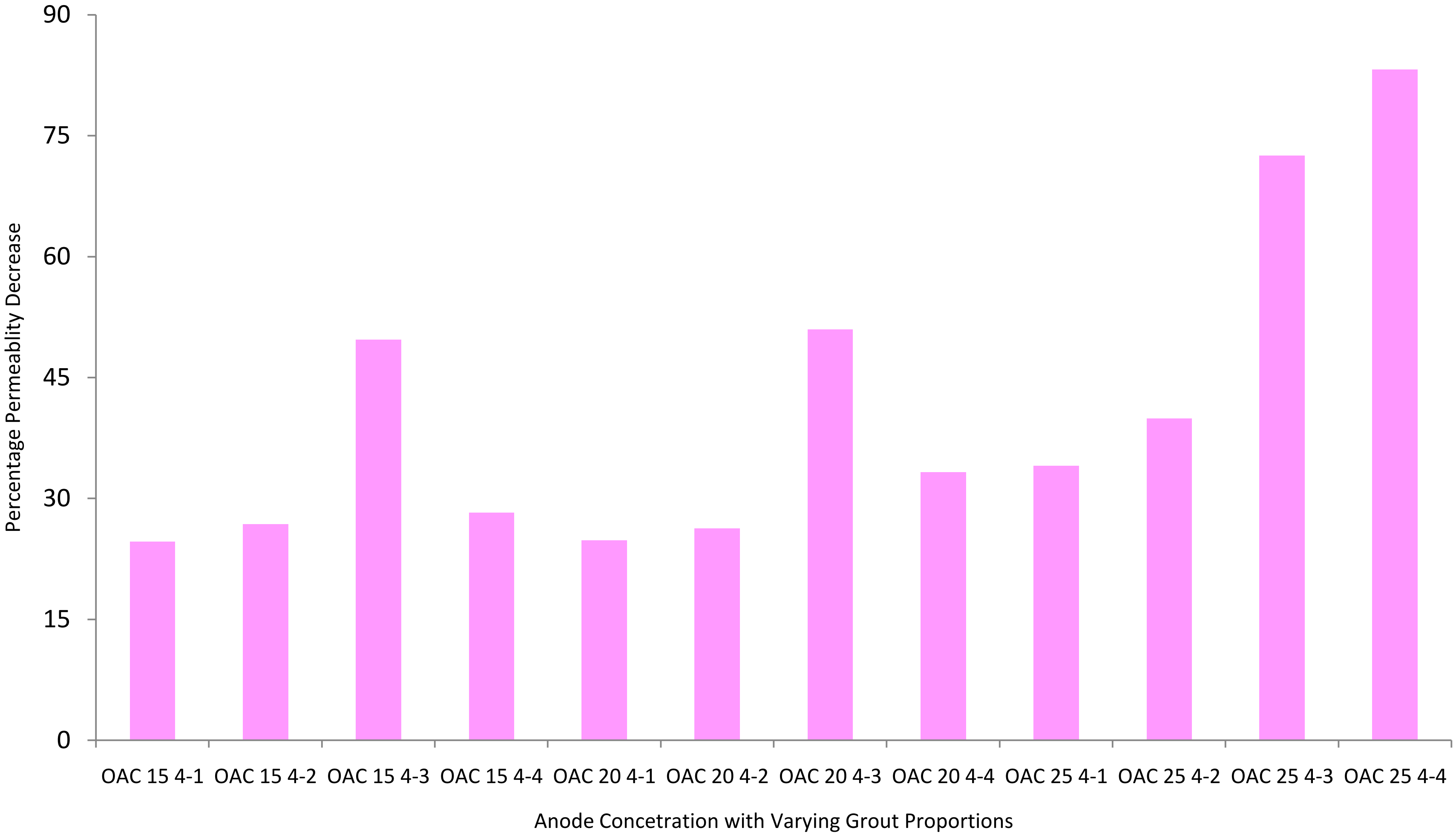


Fig. 4.15 Comparison of Permeability – Effect of Anode Concentration (Soil 4)

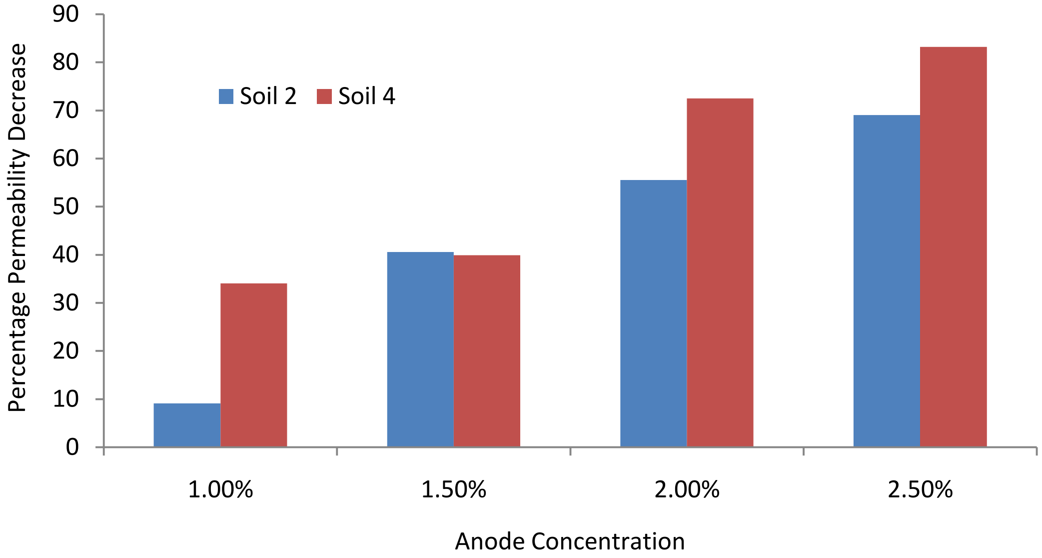


Fig. 4.16 Comparison of Permeability – Effect of Anode Concentration on Various Soils

Table 4.11 Effect of Anode Concentration on UCS and Permeability (Post Process-Soil 2)

Experiment Designation	OAC 2-1	OAC 2-2	OAC 2-3	OAC 2-4
$UCS_{postprocess}$ (kg/cm^2)	0.828	0.861	0.895	0.924
$k_{initial}$ (cm/sec)	1.98E-02	1.98E-02	1.98E-02	1.98E-02
k_{final} (cm/sec)	1.80E-02	1.18E-02	8.80E-03	6.13E-03

Table 4.12 Effect of Anode Concentration on UCS and Permeability (Post Process-Soil 4)

Experiment Designation	$UCS_{postprocess}$ (kg/cm^2)	$k_{initial}$ (cm/sec)	k_{final} (cm/sec)
OAC 15 4-1	0.841	1.38E-06	1.04E-06
OAC 15 4-2	0.831	1.38E-06	1.01E-06
OAC 15 4-3	1.557	1.38E-06	6.94E-07
OAC 15 4-4	1.543	1.38E-06	9.90E-07
OAC 20 4-1	0.868	1.38E-06	1.04E-06
OAC 20 4-2	0.983	1.38E-06	1.02E-06
OAC 20 4-3	1.703	1.38E-06	6.77E-07
OAC 20 4-4	1.644	1.38E-06	9.21E-07
OAC 25 4-1	1.016	1.38E-06	9.10E-07
OAC 25 4-2	1.088	1.38E-06	8.29E-07
OAC 25 4-3	2.056	1.38E-06	3.79E-07
OAC 25 4-4	2.082	1.38E-06	2.32E-07

4.6.1.5 Effect of Reactor Size

Analysis: For this phase, four different sizes of reactors were used as mentioned in Table 4.3. Figure 4.17 shows the comparative plot for percentage decrease in permeability in the study. Table 4.13 shows the post treatment value for UCS and permeability with variation of reactor size. The value of UCS shows an appreciable change with change in the reactor size.

Discussion: This increase can be ascribed to increase in efficiency of grouting due to a larger front being available for the grout flow as well as movement of ions. This same trend though is not very clearly visible in case of permeability.

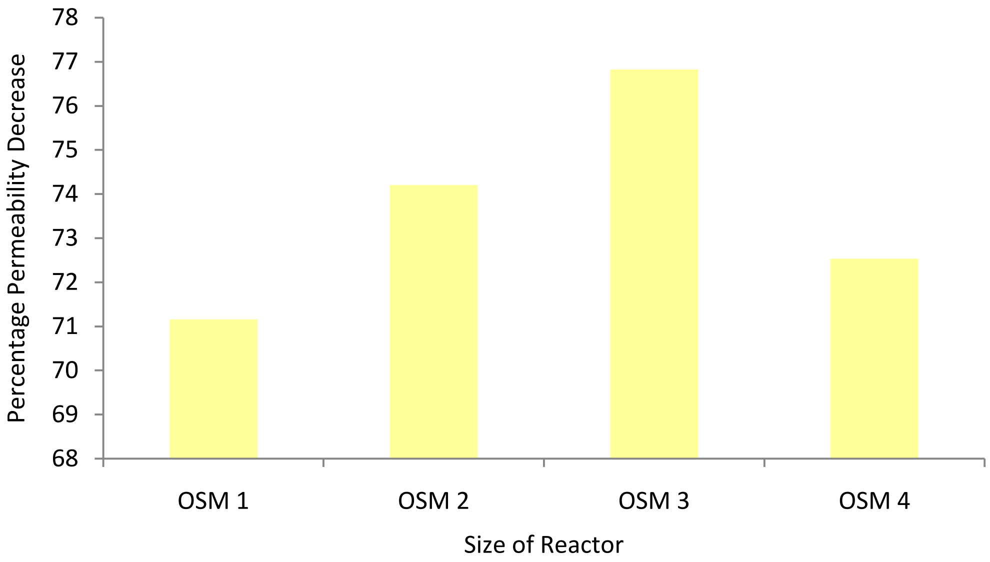


Fig. 4.17 Comparison of Permeability – Effect of Reactor Size

Table 4.13 Effect of Reactor Size on UCS and Permeability (Post Process)

Experiment Designation	OSM1	OSM2	OSM3	OSM4
$UCS_{postprocess}$ (kg/cm^2)	0.836	0.910	1.388	2.056
$k_{initial}$ (cm/sec)	1.38E-06	1.38E-06	1.38E-06	1.38E-06
k_{final} (cm/sec)	3.98E-07	3.56E-07	3.2E-07	3.79E-07

4.6.1.6 Effect of Voltage Gradient

Analysis: Figure 4.18 shows the comparison of percentage of permeability decrease with varying voltage gradient performed on Soils 1,2,3 and 4, whereas figure 4.19 shows the same plot for voltage gradient by varying the grout concentration performed on Soil 4. Soil 2 (SW) shows the maximum improvement with respect to permeability, the reason behind this improvement can be the greater initial flow of grout due to larger interconnected voids. From the plot for Soil 4, it is noted that varying the grout concentration with applied voltage gradient, grout with 30% sodium silicate shows comparatively higher improvement which diminishes at higher applied voltage. Though the higher voltage gradient causes the ionic mobility to increase but the higher concentration of the grout increases the viscosity of the grout to flow and reduces the quantity of water available for hydrolysis, which causes the reduction in improvement. Figure 4.20 shows the percentage of permeability plot for Soil 4 tested using Open Reactor 2 instead of Open Reactor 4, here the percentage improvement is higher with increase in the voltage gradient i.e. applied voltage for a given electrode spacing. Table 4.14, 4.15 and 4.16 shows the post process values of UCS and permeability for all the experiments carried out under this phase of work. It is interesting to notice the high value of UCS obtained for Soil 1 (Table 4.14) but the virgin soil itself has a very high UCS value being a CH type of soil. Though the soil was filled on wet side for the required density to be maintained in the mould but with application of DC supply, drying of the soil occurs with increased applied voltage.

Table 4.14 Effect of Voltage Gradient on UCS and Permeability (Post Process)

Experiment Designation	$UCS_{postprocess}$ (kg/cm^2)	$k_{initial}$ (cm/sec)	k_{final} (cm/sec)
OVG25 1-1	4.943	5.32E-06	5.21E-06
OVG25 1-2	5.464	5.32E-06	5.27E-06
OVG25 2-1	1.028	1.98E-02	4.07E-03
OVG25 2-2	1.094	1.98E-02	3.73E-03
OVG25 3-1	1.030	1.94E-02	8.33E-03
OVG25 3-2	1.133	1.94E-02	8.24E-03
OVG25 4-1	1.611	1.38E-06	4.09E-07
OVG25 4-2	2.056	1.38E-06	3.79E-07

Discussion: Electro-osmotic migration is a dominant transport process in case of electrokinetic grouting. The increase in the voltage gradient indirectly implies the increase in the electric potential applied across a reactor, which within the reactor soil would increase in the ionic mobility thereby inducing higher electro-osmotic flow. This causes a better grout gel formation within the soil mass as well as a deeper front migration counteracting the low pH conditions formed due to the electrolysis of water, further a cause of strength increment. These results suggest that it is feasible to apply higher potential gradients to efficiently grout the soil in a short time. However, the distance between the electrodes becomes longer in field tests compared to lab tests. Therefore, it is necessary to extend the treatment time.

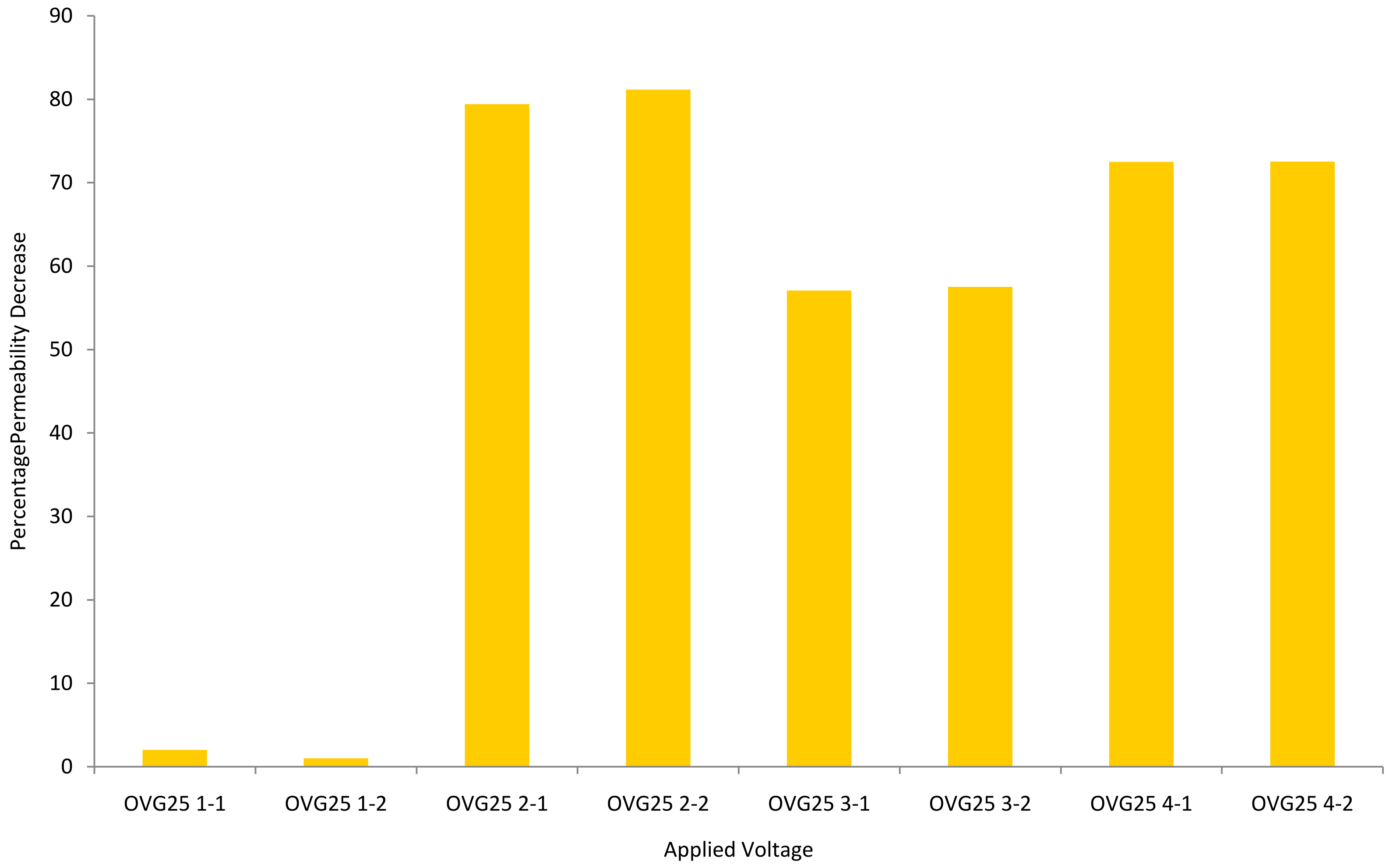


Fig. 4.18 Comparison of Permeability – Effect of Voltage Gradient for Various Soils

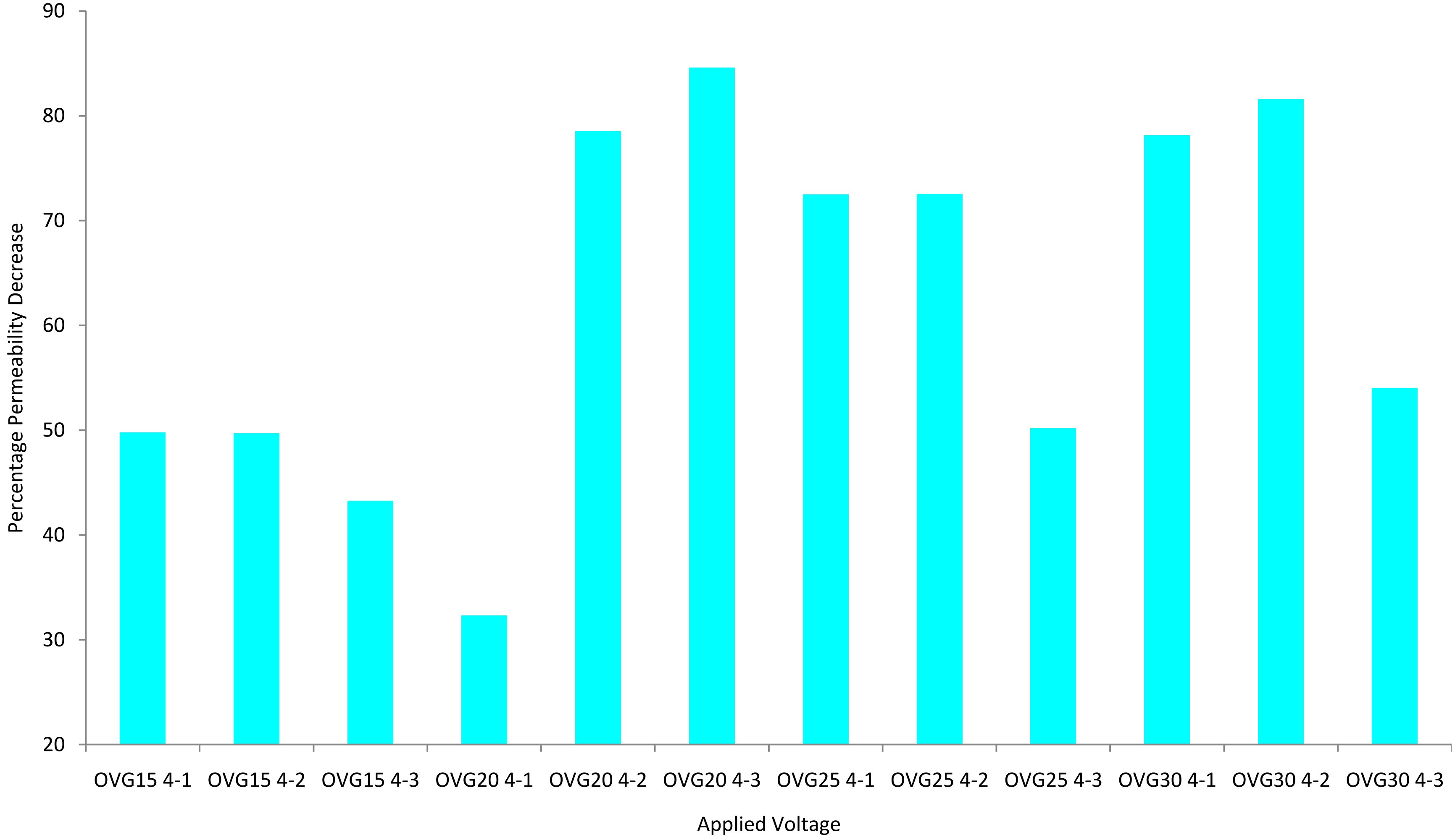


Fig. 4.19 Comparison of Permeability – Effect of Voltage Gradient for Various Grout Mix (Soil 4)

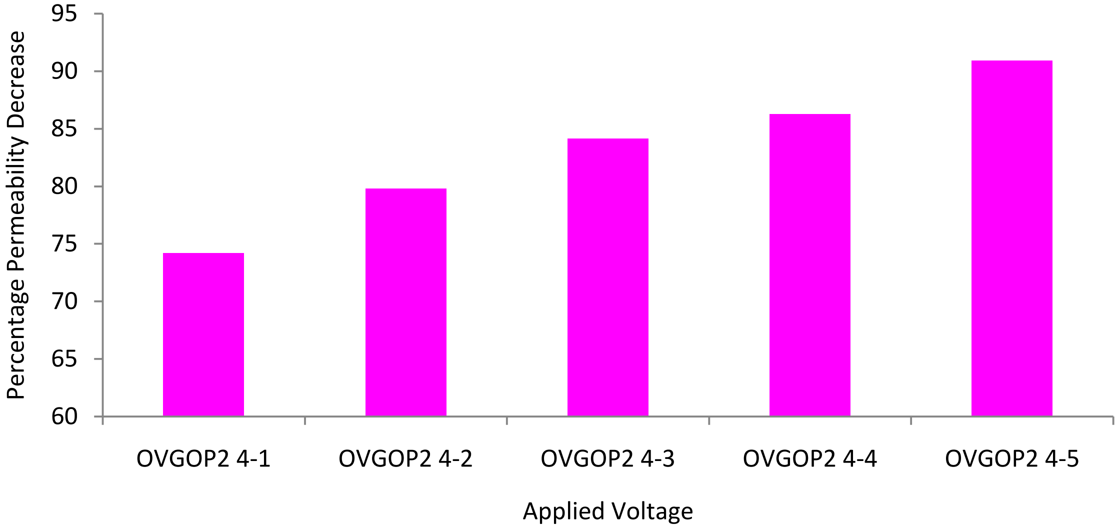


Fig. 4.20 Comparison of Permeability – Effect of Voltage Gradient (Open Reactor 2)

Table 4.15 Effect of Voltage Gradient on UCS and Permeability (Post Process-Various Grout Mix)

Experiment Designation	$UCS_{postprocess}$ (kg/cm^2)	$k_{initial}$ (cm/sec)	k_{final} (cm/sec)
OVG15 4-1	1.513	1.38E-06	6.93E-07
OVG15 4-2	1.557	1.38E-06	6.94E-07
OVG15 4-3	1.100	1.38E-06	7.83E-07
OVG20 4-1	1.558	1.38E-06	9.34E-07
OVG20 4-2	2.158	1.38E-06	2.96E-07
OVG20 4-3	1.292	1.38E-06	2.13E-07
OVG25 4-1	1.611	1.38E-06	4.09E-07
OVG25 4-2	2.056	1.38E-06	3.79E-07
OVG25 4-3	1.268	1.38E-06	6.87E-07
OVG30 4-1	2.002	1.38E-06	3.02E-07
OVG30 4-2	2.217	1.38E-06	2.54E-07
OVG30 4-3	1.306	1.38E-06	6.34E-07

Table 4.16 Effect of Voltage Gradient on UCS and Permeability (Post Process-Open Reactor 2)

Experiment Designation	$UCS_{postprocess}$ (kg/cm^2)	$k_{initial}$ (cm/sec)	k_{final} (cm/sec)
OVGOP2 4-1	0.910	1.38E-06	3.56E-07
OVGOP2 4-2	0.993	1.38E-06	2.79E-07
OVGOP2 4-3	1.060	1.38E-06	2.19E-07
OVGOP2 4-4	1.110	1.38E-06	1.90E-07
OVGOP2 4-5	1.188	1.38E-06	1.26E-07

4.6.1.7 Effect of Reactant Type and Its Concentration

Analysis: In order to understand the effect of reactant and its concentration, nine experiments were conducted. In this phase three reactants ($CaCl_2$, $Al_2(SO_4)_3$ and $NaHCO_3$) were used with different concentration (2%, 3% and 4%). Figure 4.21 and 4.22 shows the % permeability improvement plots post electrokinetic grouting. For the reactant, calcium chloride experiments ORCCa 4-1, ORCCa 4-2 and ORCCa 4-3 were conducted. The maximum decrease in permeability was observed for ORCCa 4-3 (7.62E-07 cm/sec) and minimum decrease in permeability was observed for ORCCa 4-1 (8.64E-07 cm/sec). In case of sodium bi-carbonate being used as a hardener reactant the maximum decrease in permeability observed was in ORCNa 4-1 i.e. 9.07E-07 cm/sec. For other two experiments the values were 7.68E-07 cm/sec and 6.52E-07 cm/sec for ORCNa 4-2 and ORCNa 4-3 respectively, whereas the use of aluminium sulphate as reactant showed the minimum decrease in permeability in case of ORCAl 4-1 (8.04E-07 cm/sec) and maximum decreased value in permeability was 6.26E-07cm/sec (ORCAl 4-3). Table 4.17 shows the post treatment UCS values for all the experiments with maximum improvement being shown when using 3% aluminium sulphate (3.115kg/cm^2). All the three reactants showed maximum improvement with 3% concentration which was noticed when the trial mix of grout was prepared before taking up the study.

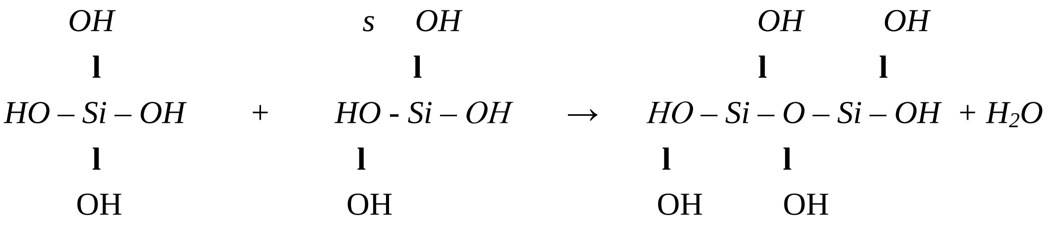
Discussion: It is well known that silicates only hydrolysis followed by condensation form gels. The three reactants from the anode (calcium chloride, aluminium sulphate and sodium bi carbonate) react with sodium silicate from the cathode, undergo hydrolysis followed by condensation and finally form a gel which imparts strength to the soil. In case of $NaHCO_3$, the HCO_3^- radical, which is acidic in nature, enhances the rate of hydrolysis of Na_2SiO_3.

HYDROLYSIS REACTION

$$Na_2O.SiO_2.H_2O + 2NaHCO_3 \rightarrow Si(OH)_{42} + 2Na_2CO_3 \qquad \text{----------- (1)}$$

$$Na_2O.SiO_2 + YH_2O + 2NaHCO_3 \rightarrow SiO_2 + (Y+1)H_2O + 2Na_2CO_3 \text{ ----------- (2)}$$

CONDENSATION REACTION



$$HO-\underset{OH}{\overset{OH}{Si}}-OH + HO-\underset{OH}{\overset{OH}{Si}}-OH \rightarrow HO-\underset{OH}{\overset{OH}{Si}}-O-\underset{OH}{\overset{OH}{Si}}-OH + H_2O \qquad \text{------(3)}$$

Silicic acid

OR

$$\equiv Si\text{-}OH + HO\text{-}Si\equiv \rightarrow \equiv Si\text{-}O\text{-}Si\equiv + H_2O$$

Silicic acid Silicic acid growing silica network (gel)

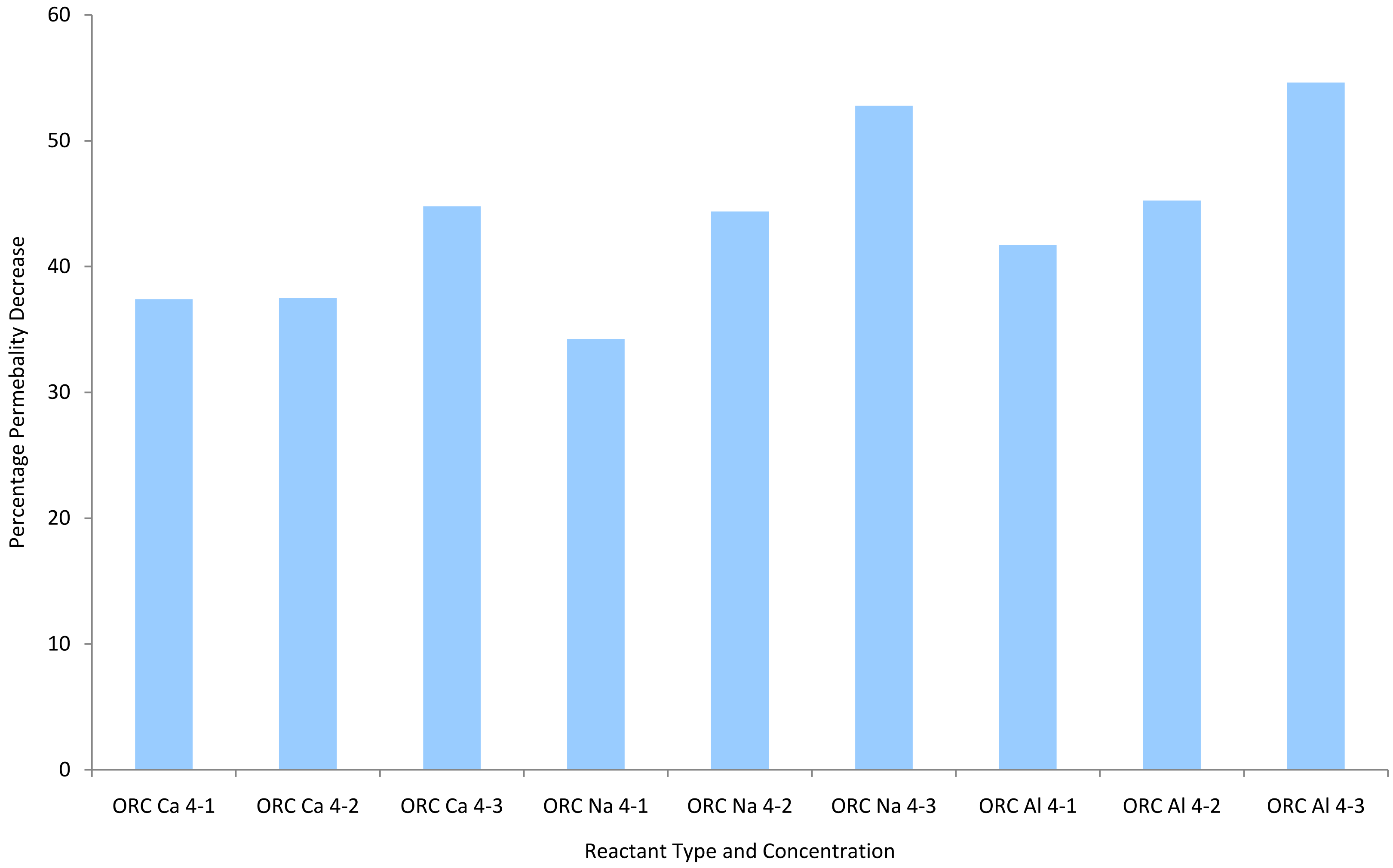


Fig. 4.21 Comparison of Permeability – Effect of Reactant Type

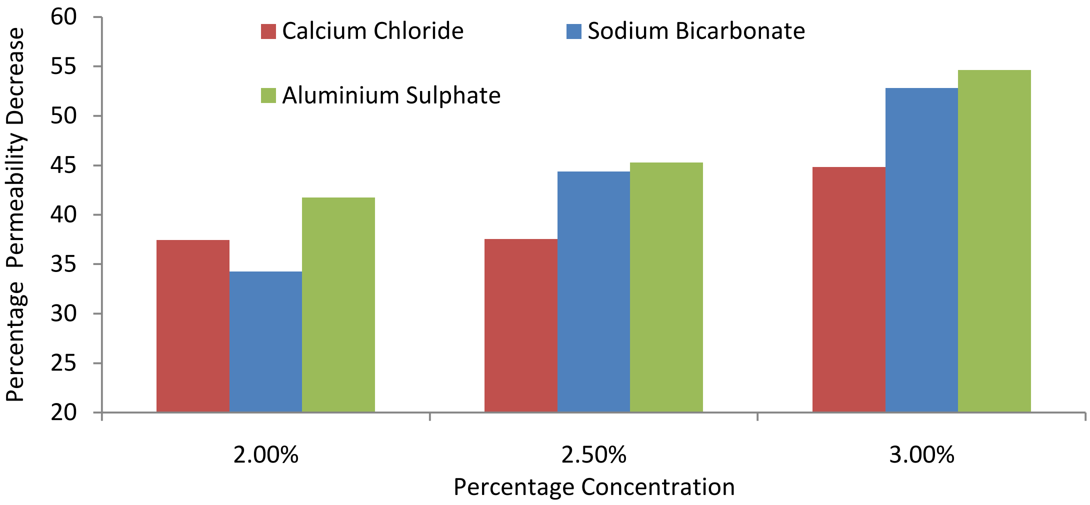


Fig. 4.22 Comparison of Permeability – Effect of Reactant Concentration

In case of $CaCl_2$, the $CaCl_2$ reacts with Na_2SiO_3 to form $CaSiO_3$ as per the equation 4

$$Na_2SiO_3 + CaCl_2 \rightarrow CaSiO_3 + 2NaCl \text{ --------------- } (4)$$

And this $CaSiO_3$ reacts with water present to form hydrated compounds of very low solubility (calcium silicate hydrates) and soluble calcium hydroxide. (Eq. 5 and 6)

$$2(3CaO.SiO_2) + 6H_2O \rightarrow 3CaO.2SiO_2.3H_2O + 3Ca(OH)_2 \text{ ----------------}(5)$$

$$2(2CaO.SiO_2) + 4H_2O \rightarrow 3CaO.2SiO_2.3H_2O + Ca(OH)_2 \text{ -------------------}(6)$$

Similarly $Al_2(SO_4)_3$ reacts with Na_2SiO_3 to form its corresponding silicate, $Al_2(SiO_3)_3$ Eq. 7.

$$Al_2(SO_4)_3 + 3Na_2SiO_3 \rightarrow Al_2(SiO_3)_3 + 3Na_2SO_4 \text{-----------------}(7)$$

Both $CaSiO_3$ and $Al_2(SiO_3)_3$ undergo hydrolysis (Eq.2) followed by condensation (Eq. 3) to yield a growing silica network as shown in case of Na_2SiO_3 (Eq. 3).

Table 4.17 Effect of Reactant Type on UCS and Permeability (Post Process)

Experiment Designation	UCSpostprocess (kg/cm^2)	$k_{initial}$ (cm/sec)	k_{final} (cm/sec)
ORCCa 4-1	0.816	1.38E-06	8.64E-07
ORCCa 4-2	0.890	1.38E-06	8.63E-07
ORCCa 4-3	1.261	1.38E-06	7.62E-07
ORCNa 4-1	1.929	1.38E-06	9.07E-07
ORCNa 4-2	2.225	1.38E-06	7.68E-07
ORCNa 4-3	2.596	1.38E-06	6.52E-07
ORCAl 4-1	0.755	1.38E-06	8.04E-07
ORCAl 4-2	2.744	1.38E-06	7.56E-07
ORCAl 4-3	3.115	1.38E-06	6.26E-07

4.6.1.8 Effect of Low Frequency AC Supply

Analysis: Figure 4.23 shows the % permeability change for four different frequency of AC supply adopted for the study. The minimum improvement in permeability was found when AC supply was maximum 1 Hz (1.05E-06 cm/sec). OLAC 1 exhibited maximum improvement in permeability i.e. the permeability value decreased from 1.38E-06 to 9.6E-07cm/sec. The maximum UCS was obtained when the frequency was 0.25 Hz i.e. OLAC 1 compared to other higher frequencies though the value was less compared to the standard DC supply. The UCS varied from 0.926kg/cm^2 to 0.739kg/cm^2 in the four experiments (Table 4.18).

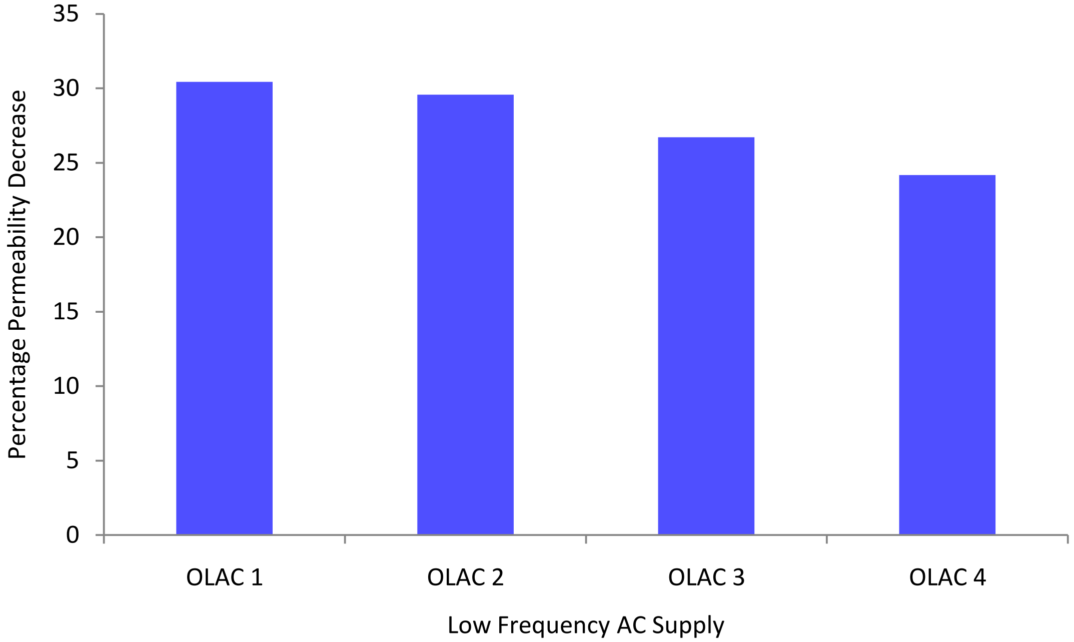


Fig. 4.23 Comparison of Permeability – Effect of Low Frequency AC Supply

Table 4.18 Effect of Low Frequency AC Supply on UCS and Permeability (Post Process)

Experiment Designation	OLAC1	OLAC2	OLAC3	OLAC4
$UCS_{postprocess}$ (kg/cm^2)	0.926	0.779	0.748	0.739
$k_{initial}$ (cm/sec)	1.38E-06	1.38E-06	1.38E-06	1.38E-06
k_{final} (cm/sec)	9.6E-07	9.72E-07	1.01E-06	1.05E-06

Discussion: The observed appreciable decrease in the UCS strength in case of AC supply rules out possibility of the replacement of DC supply. The remediation using low frequency AC supply is relatively less as compared to the DC supply. When using an AC supply at low frequency causes alternating of cathode and anode once every four second. This alternating change of the polarity hinders the movement of ions uniformly along the sample, allowing neither electromigration and/or migration potential to develop completely. The changing polarity also hinders the electrolysis of water as well as movement of neither the H^+ nor the OH^- ions causing chaos at either electrodes resulting in inefficiency of grouting. Also, as we increase the frequency of the supply, inertial effects in the fluid start to retard the motion of the fluid in the interconnected voids which essentially form capillaries. Consequently, the ratio of the responding phenomenon, i.e. electro-osmotic flow to the driving force, reduces.

4.6.1.9 Effect of Grout Concentration

Analysis: Four different grout concentrations i.e. 15%, 20%, 25% and 30% (volume by volume) sodium silicate in water were used to treat Soil 1, 2, 3 and 4. An extensive study was selected for this phase since the grout concentration can have different effects on soils depending on their composition as well as the voltage gradient applied. The amount of calcium chloride was kept constant at 2% w/v for all the experiments in this phase. Figure 4.24, 4.25, 4.26 and 4.27 show the percentage permeability plot for Soil 1, 2, 3 and 4 respectively with different voltage gradients and grout proportions. Soil 1(CH) does not show any appreciable change in the permeability as the grout flow is very difficult in this type of soil under such small voltage gradient since overcoming the cohesive force to hydrolyze the water particle required for electro-osmosis flow as well as the electromigration of the sodium ions becomes very difficult. For Soil 2 and 3 both SW type of soil, there is reduction in the permeability value from 1.98E-02 to 3.45E-03 and 1.94E-02 to 7.84E-03 respectively. Soil 4(ML) shows higher improvement in permeability when the voltage applied is 12.5V as compared to 37.5V. All the experiments showed maximum improvement with 30% grout concentration irrespective of the applied voltage or soil type.

Table 4.19, 4.20, 4.21 and 4.22 shows the post treatment UCS values and permeability values for Soil 1, 2, 3 and 4. Maximum value of UCS was observed in Soil 1, wherein the UCS value increased to 5.619kg/cm^2, Soil 2 increased to 1.118kg/cm^2, Soil 3 increased to 1.146 kg/cm^2 and for Soil 4 increased to 2.217 kg/cm^2.

Discussion: Addition of higher concentration of grout i.e. more sodium silicate led to better improvement in the permeability values, one cannot claim that using such stabilizer alone is good enough to be selected as main injecting grout. This is because of its solubility after immersing through water. It means after injection and finishing the chemical reaction, if the adjust environment become fully saturated, the bonding between soil structures probably will be lost with the grout being washed out of the pores. As the concentration of sodium silicate is increased in the cathode compartment its viscosity increases. Although this increase in viscosity reduces the flow rate of the solution, in turn increases the quantity of sodium silicate available for reaction with calcium chloride thereby increasing the UCS due to the gellation of calcium silicate as is observed. Since silicate grouts typically contain large amounts of water, they may exhibit shrinkage or syneresis. While this is most commonly found in laboratory gelling studies where the grout is not incorporated in the soil matrix, hardening systems which exhibit greater than 30% shrinkage should be avoided. However, sodium silicate is kind of a gel producer and further investigation in cohesive base soil is required to understand the improvement behavior when sodium silicate grout system is considered as a main stabilizer. Moreover, temperature and length of time curing at which curing shall take place have a significant influence on the amount of strength developed.

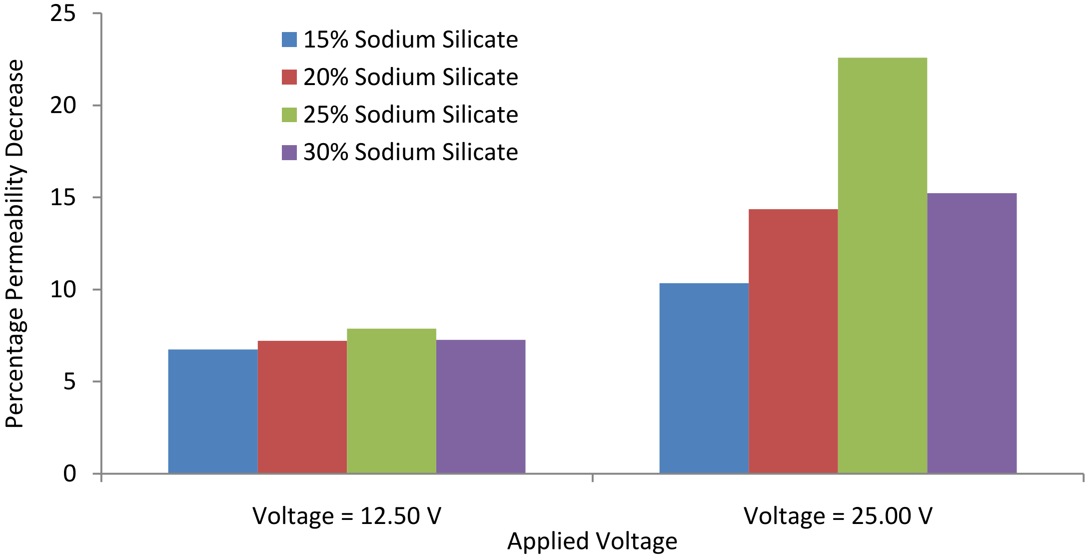


Fig. 4.24 Comparison of Permeability – Effect of Grout Concentration (Soil 1)

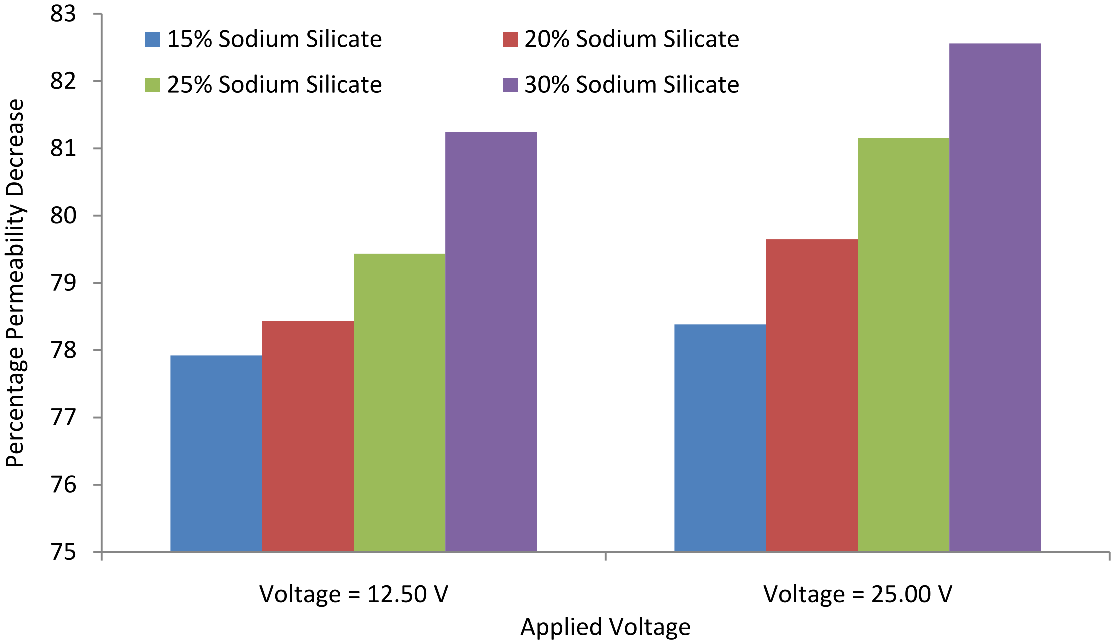


Fig. 4.25 Comparison of Permeability – Effect of Grout Concentration (Soil 2)

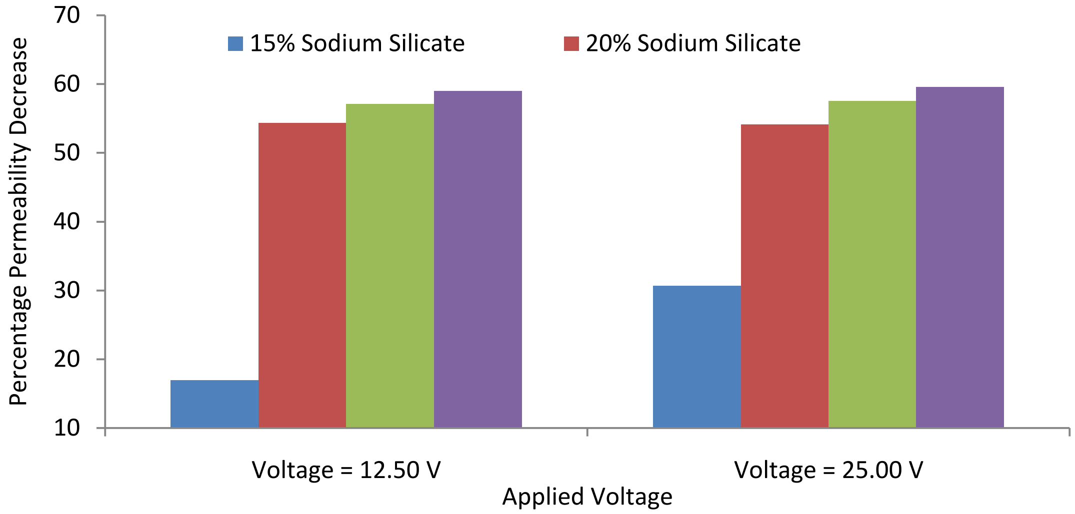


Fig. 4.26 Comparison of Permeability – Effect of Grout Concentration (Soil 3)

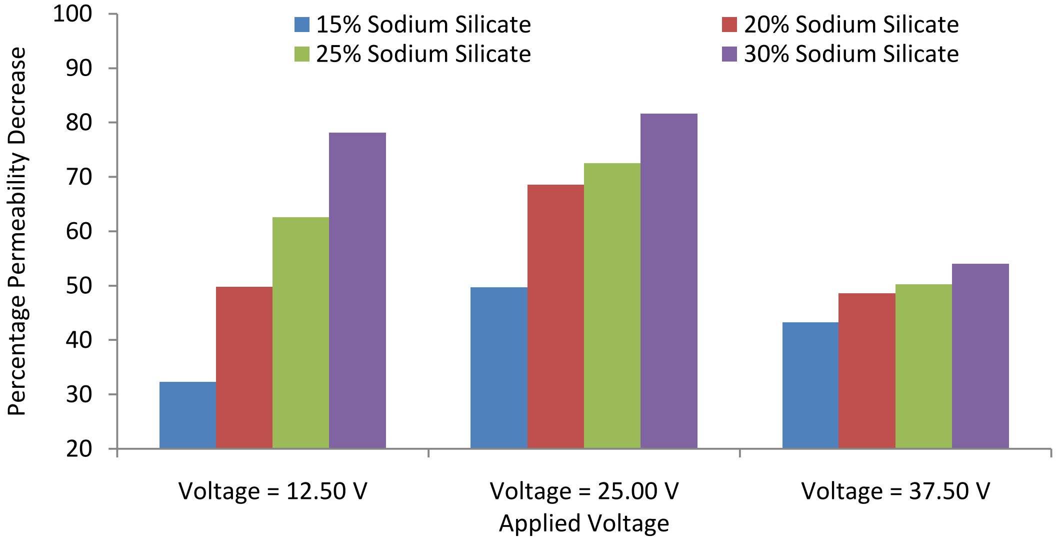


Fig. 4.27 Comparison of Permeability – Effect of Grout Concentration (Soil 4)

Table 4.19 Effect of Grout Concentration on UCS and Permeability

(Post Process – Soil 1)

Experiment Designation	$UCS_{postprocess}$ (kg/cm^2)	$k_{initial}$ (cm/sec)	k_{final} (cm/sec)
OGC 0.5 1-1	4.862	5.32E-06	4.96E-06
OGC 0.5 1-2	5.083	5.32E-06	4.94E-06
OGC 0.5 1-3	4.943	5.32E-06	4.9E-06
OGC 0.5 1-4	5.524	5.32E-06	4.93E-06
OGC 1 1-1	5.063	5.32E-06	4.77E-06
OGC 1 1-2	5.193	5.32E-06	4.56E-06
OGC 1 1-3	5.464	5.32E-06	4.12E-06
OGC 1 1-4	5.619	5.32E-06	4.51E-06

Table 4.20 Effect of Grout Concentration on UCS and Permeability (Post Process – Soil 2)

Experiment Designation	$UCS_{postprocess}$ (kg/cm^2)	$k_{initial}$ (cm/sec)	k_{final} (cm/sec)
OGC 0.5 2-1	0.831	1.98E-02	4.37E-03
OGC 0.5 2-2	0.926	1.98E-02	4.27E-03
OGC 0.5 2-3	1.028	1.98E-02	4.07E-03
OGC 0.5 2-4	1.108	1.98E-02	3.71E-03
OGC 1 2-1	0.904	1.98E-02	4.28E-03
OGC 1 2-2	0.936	1.98E-02	4.03E-03
OGC 1 2-3	1.094	1.98E-02	3.73E-03
OGC 1 2-4	1.118	1.98E-02	3.45E-03

Table 4.21 Effect of Grout Concentration on UCS and Permeability (Post Process – Soil 3)

Experiment Designation	$UCS_{postprocess}$ (kg/cm^2)	$k_{initial}$ (cm/sec)	k_{final} (cm/sec)
OGC 0.5 3-1	0.839	1.94E-02	1.61E-02
OGC 0.5 3-2	0.945	1.94E-02	8.86E-03
OGC 0.5 3-3	1.030	1.94E-02	8.33E-03
OGC 0.5 3-4	1.050	1.94E-02	7.96E-03
OGC 1 3-1	0.909	1.94E-02	1.35E-02
OGC 1 3-2	1.098	1.94E-02	8.90E-03
OGC 1 3-3	1.133	1.94E-02	8.24E-03
OGC 1 3-4	1.146	1.94E-02	7.84E-03

Table 4.22 Effect of Grout Concentration on UCS and Permeability (Post Process – Soil 4)

Experiment Designation	$UCS_{postprocess}$ (kg/cm^2)	$k_{initial}$ (cm/sec)	k_{final} (cm/sec)
OGC 0.5 4-1	1.513	1.38E-06	9.34E-07
OGC 0.5 4-2	0.996	1.38E-06	6.93E-07
OGC 0.5 4-3	1.611	1.38E-06	5.17E-07
OGC 0.5 4-4	2.002	1.38E-06	3.02E-07
OGC 1 4-1	1.557	1.38E-06	6.94E-07
OGC 1 4-2	2.158	1.38E-06	4.34E-07
OGC 1 4-3	2.056	1.38E-06	3.79E-07
OGC 1 4-4	2.217	1.38E-06	2.54E-07
OGC 1.5 4-1	1.100	1.38E-06	7.83E-07
OGC 1.5 4-2	1.292	1.38E-06	7.09E-07
OGC 1.5 4-3	1.268	1.38E-06	6.87E-07
OGC 1.5 4-4	1.306	1.38E-06	6.34E-07

4.6.2 Closed Reactor

4.6.2.1 Effect of Soil Composition

- **Closed Reactor – Soil Composition 1 (CSC 1)**

Analysis: Figure 4.28 shows the comparison of initial and final vane shear strength of soil at constant water content along the length of the sample. The vane shear strength increased from initial value of 0.022 kg/cm^2 and varied from 0.026 kg/cm^2 to 0.053 kg/cm^2.

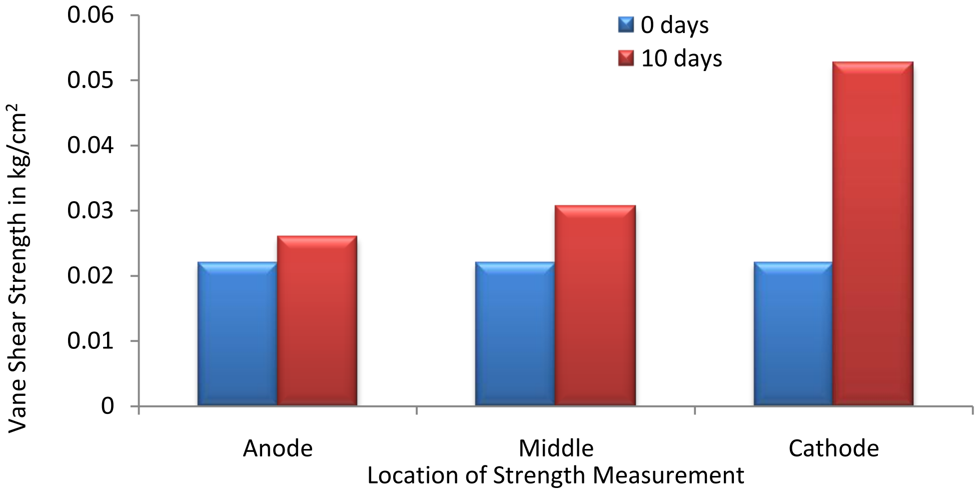


Fig. 4.28 Comparison of initial and final vane shear strength of soil at different locations (CSC 1)

- **Closed Reactor – Soil Composition 2 (CSC 2)**

Analysis: Figure 4.29 shows the comparison of initial and final vane shear strength of soil at constant water content along the length of the sample. The vane shear strength increased significantly from the initial value of 0.022 kg/cm^2 to 0.053 kg/cm^2.

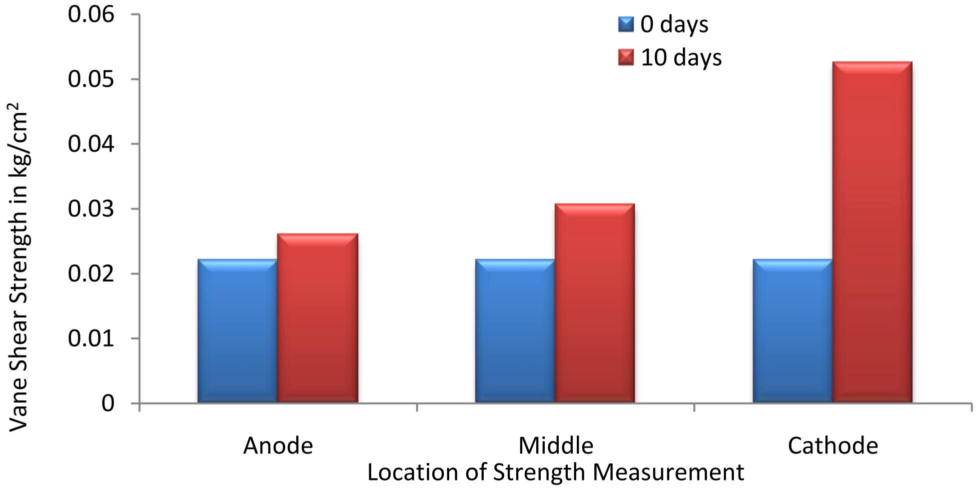


Fig. 4.29 Comparison of initial and final vane shear strength of soil at different locations (CSC 2)

- **Closed Reactor – Soil Composition 3 (CSC 3)**

Analysis: Figure 4.30 shows the comparison of initial and final vane shear strength of soil at constant water content along the length of the sample. The vane shear strength was initially 0.027 kg/cm^2. The vane shear strength increased from anode to cathode. The maximum value was 0.096 kg/cm^2.

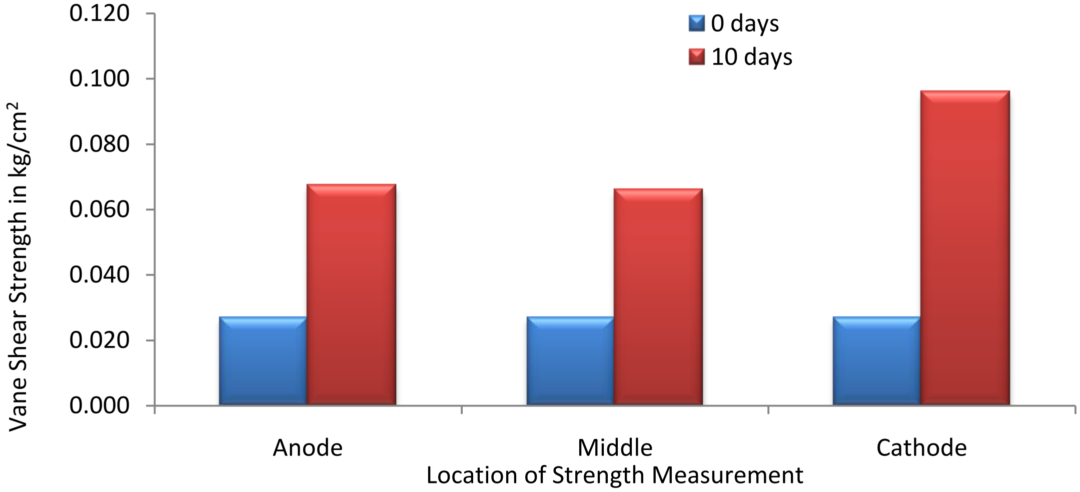


Fig. 4.30 Comparison of initial and final vane shear strength of soil at different locations (CSC 3)

- **Closed Reactor – Soil Composition 4 (CSC 4)**

Analysis: Figure 4.31 shows the comparison of vane shear strength with virgin soil. The maximum vane shear strength was found at cathode. The vane shear strength was initially 0.019 kg/cm^2. The vane shear strength at anode was noted 0.021 kg/cm^2 and at cathode it was 0.057 kg/cm^2.

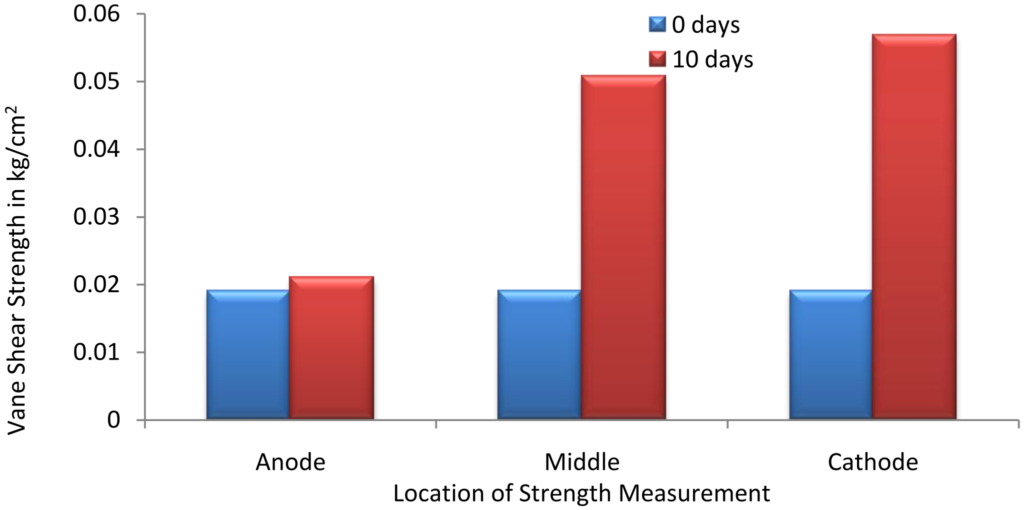


Fig. 4.31 Comparison of initial and final vane shear strength of soil at different locations (CSC 4)

- **Closed Reactor – Soil Composition 5 (CSC 5)**

Analysis: Figure 4.32 shows the comparison of initial and final vane shear strength of soil at constant water content along the length of the sample. The initial vane shear strength of Soil 5 was 0.018 kg/cm^2 and the average of all the three samples was 0.048 kg/cm^2 giving a net increase in vane shear strength by 166.66%.

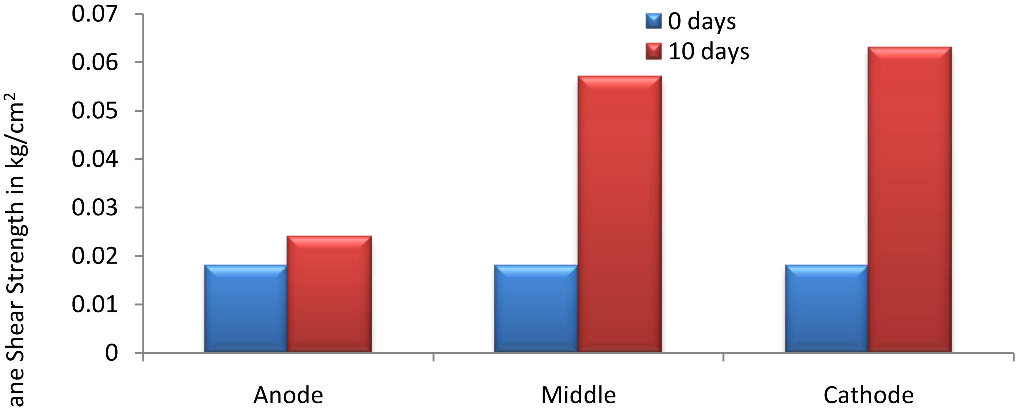


Fig. 4.32 Comparison of initial and final vane shear strength of soil at different locations (CSC 5)

- **Closed Reactor – Soil Composition 6 (CSC 6)**

Analysis: Figure 4.33 shows the comparison of initial and final vane shear strength of soil at constant water content along the length of the sample. The vane shear strength increased from initial value from 0.031 kg/cm^2 to 0.057 kg/cm^2.

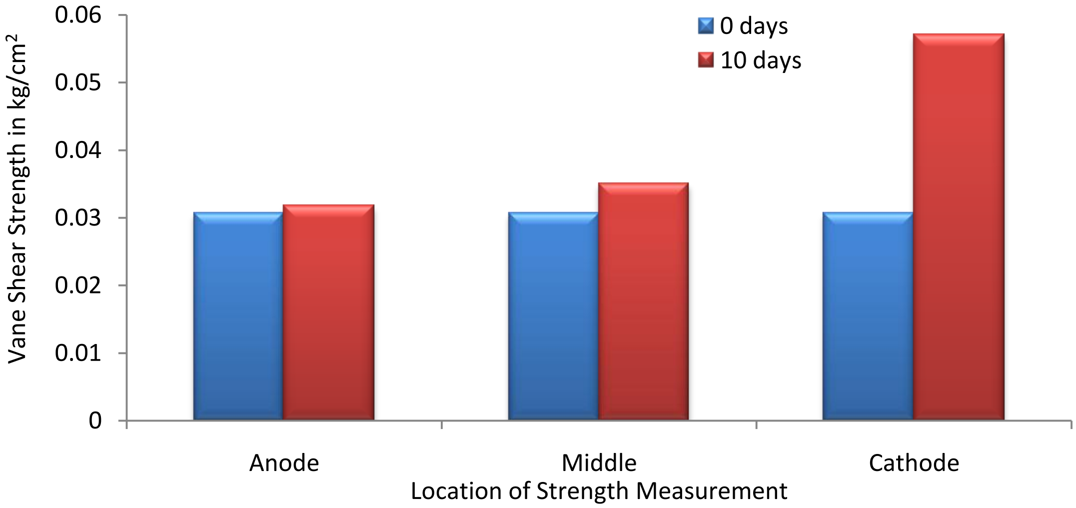


Fig. 4.33 Comparison of initial and final vane shear strength of soil at different locations (CSC 6)

Figures 4.34, 4.35 and 4.36 shows the comparative plot of vane shear strength and permeability for all the 6 types of soil samples pre and post electrokinetic grouting. The maximum vane shear strength was observed when Soil 5 was treated with electrokinetic grouting technique. The vane shear strength increased from initial value of 0.018 kg/cm^2 to 0.038 kg/cm^2. The minimum increase in vane shear strength was observed in Soil 6. The minimum vane shear strength was observed to increase from an initial value of 0.031 kg/cm^2 to 0.041 kg/cm^2. The maximum decrease in permeability was observed in Soil 2 and minimum decrease in permeability was observed in Soil 6. This may be due to highly expansive nature of the Soil 6 i.e. kaolinite. The maximum decrease in Soil 2 was 9.13E-03 cm/sec and minimum decrease in Soil 6 was 3.23E-07 cm/sec.

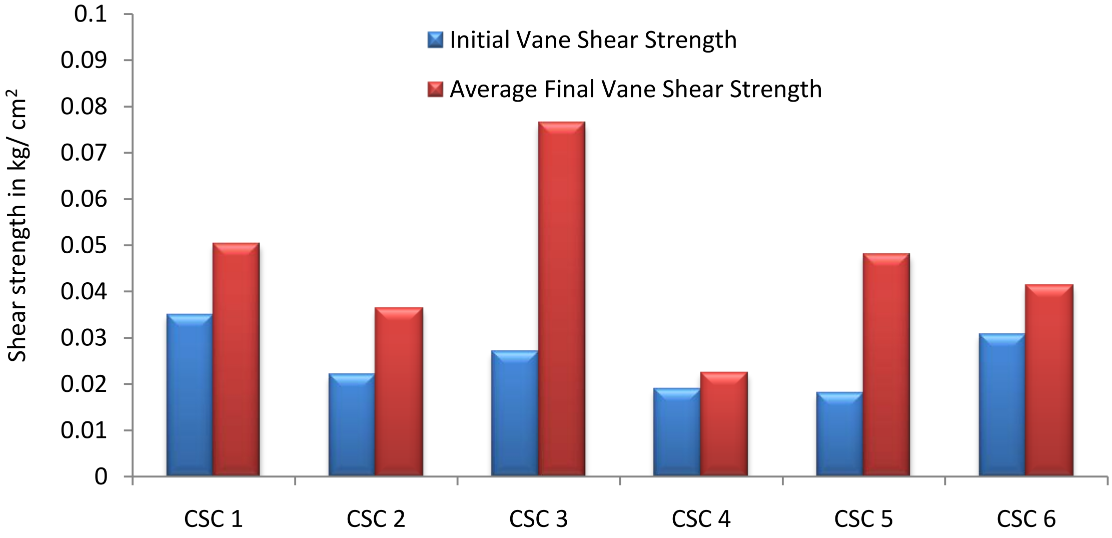


Fig. 4.34 Comparison of vane shear strength - Effect of soil composition

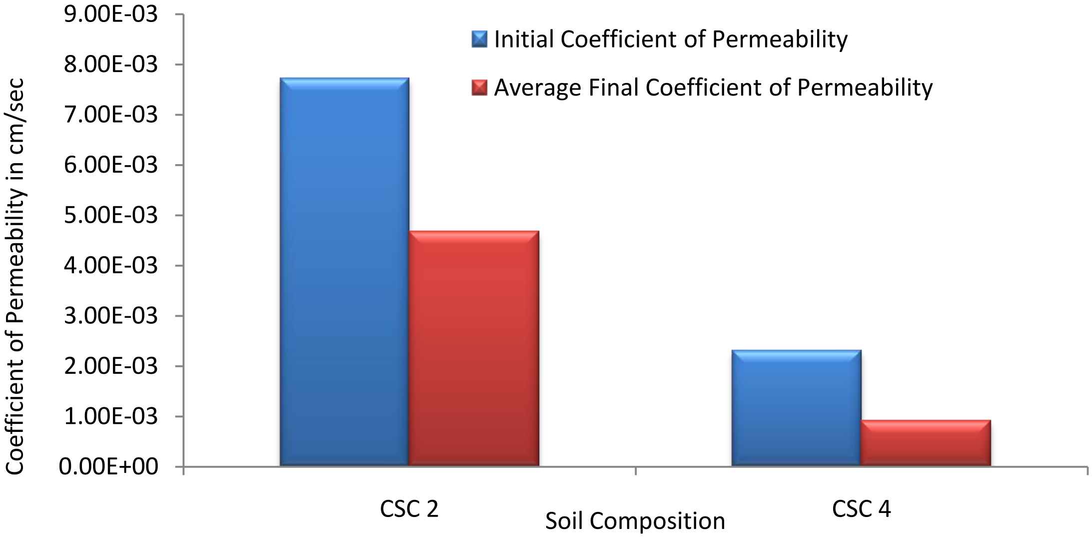


Fig. 4.35 Comparison of coefficient of permeability – Effect of soil composition

Discussion: When calcium chloride solution is injected alongwith sodium silicate solution, pozzolanic reactions happens, which lead to the formation of cementing agents, consisting of calcium silicate hydrate (CSH). The clay particles can thus be expected to be bound together and to form very stiff cemented soil. The undrained shear strength for the very stiff cemented soil could be very high, which should be comparable with undrained shear strength resulting from jet grouting. It can be concluded from the work that electrokinetic grouting is very effective method for grouting soils with very low permeability. It is also seen that it work more efficiently when used for clayey types of soils. The strength increase is maximum when the selected grout mix used with black cotton soil. The decrease in permeability for black cotton soil is relatively less since the permeability before test itself is very low. Fine silty sands can be also easily grouted with a considerable decrease in their permeability as well as appreciable increase in the strength.

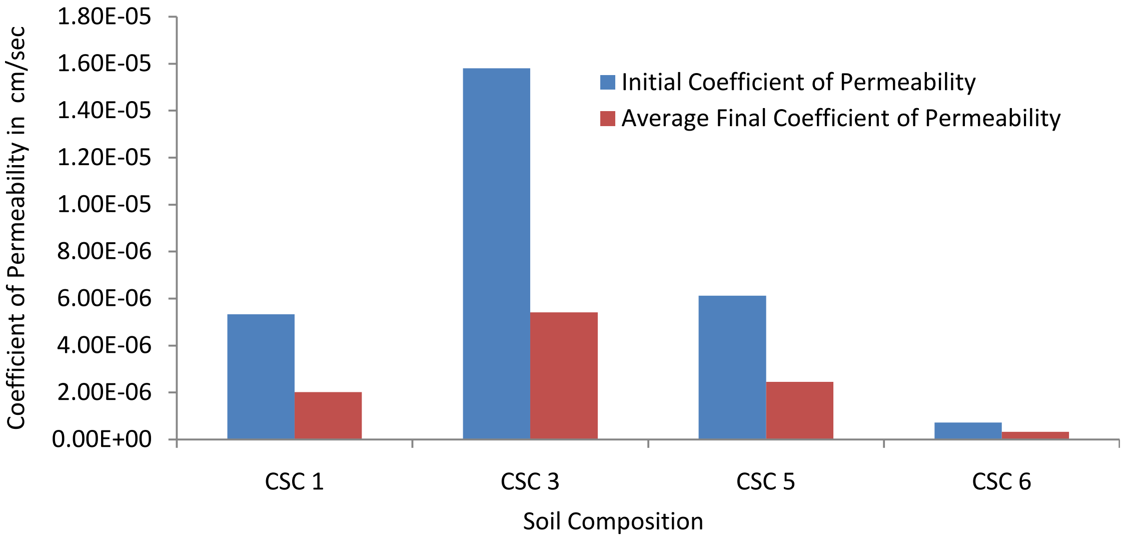


Fig. 4.36 Comparison of coefficient of Permeability – Effect of soil composition

4.6.2.2 Effect of Grout Concentration

- **Closed Reactor – Grout Concentration 1 (CGC 1)**

Analysis: Figure 4.37 shows the comparison of initial and final vane shear strength of soil at constant water content along the length of the sample. The increase in vane shear strength was 0.019 kg/cm^2 to 0.051 kg/cm^2. The average increase in vane shear strength was observed to be 0.039 kg/cm^2.

- **Closed Reactor – Grout Concentration 2 (CGC 2)**

Analysis: CGC 2 was similar to CSC 4 and the results are as discussed for CSC 4.

- **Closed Reactor – Grout Concentration 3 (GC 3)**

Analysis: Figure 4.38 shows the comparison of initial and final vane shear strength of soil at constant water content along the length of the sample. The vane shear strength increased from 0.019 kg/cm^2 to 0.078 kg/cm^2.

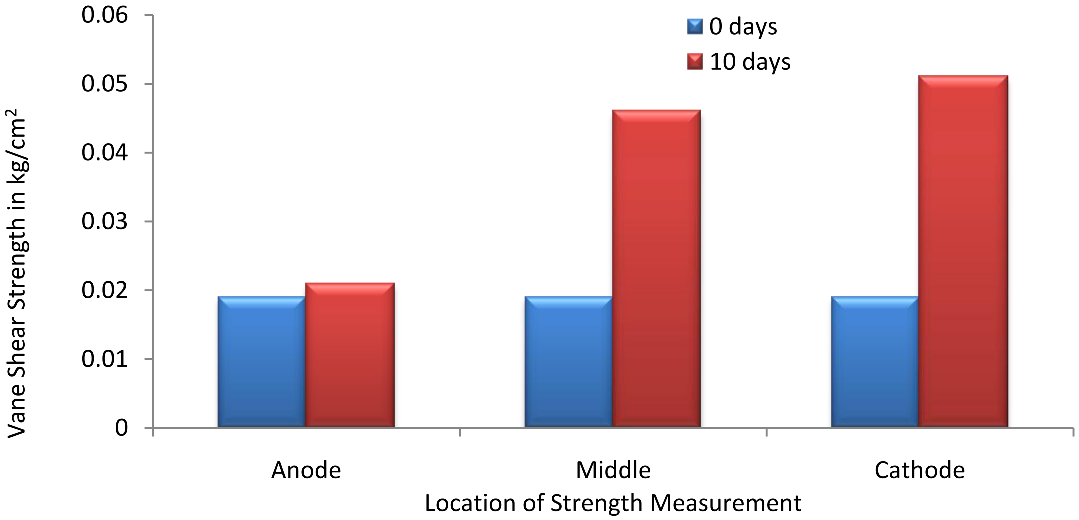


Fig. 4.37 Comparison of initial and final vane shear strength of soil at different locations (CGC 1)

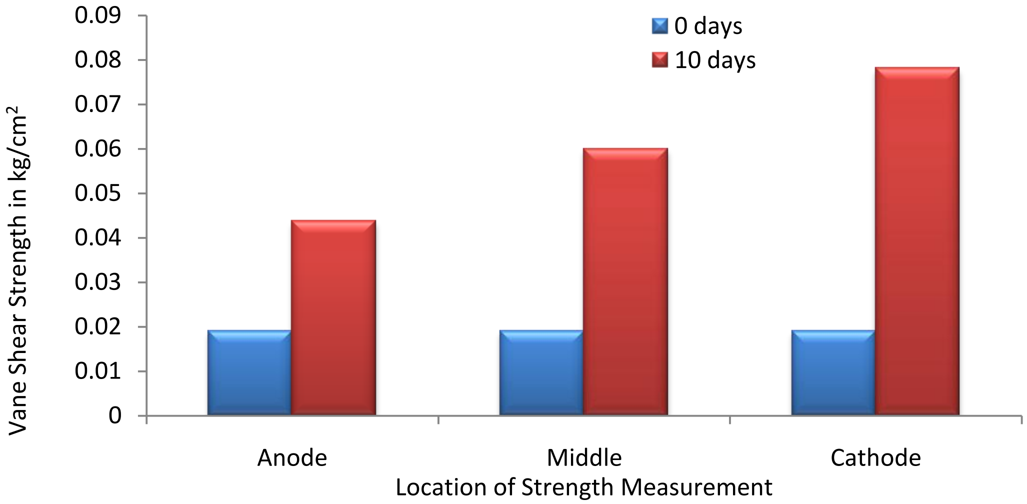


Fig. 4.38 Comparison of initial and final vane shear strength of soil at different locations (CGC 3)

For this phase, three different grout concentration of sodium silicate 20%, 25% and 30% were used to treat the Soil 3. The amount of calcium chloride was kept constant at 2% (w/v) for all the three experiments in this phase. Figures 4.39 and 4.40 show the comparative plot of vane shear strength and permeability for all the soil pre and post electrokinetic grouting of grout concentration. The maximum vane shear strength was observed when 30% (v/v) sodium silicate i.e. CGC 3 was used. The minimum vane shear strength was observed when 20% (v/v) sodium silicate i.e. CGC 1 was used. The maximum improved in strength was 233.33% i.e. from 0.018 kg/cm^2 to 0.06 kg/cm^2 and minimum improved in strength was 116.67% i.e. 0.018 kg/cm^2 to 0.039 kg/cm^2. Thus it can be concluded that the vane shear strength of the soil increases with the increase in the concentration of grout used. The maximum reduction in permeability was observed was in CGC 3. The permeability was reduced from 6.12E-06 cm/sec to 1.5E-06 cm/sec. The minimum reduce in permeability was observed in CGC 1 which was 43.67 % i.e. 3.45E-06 cm/sec.

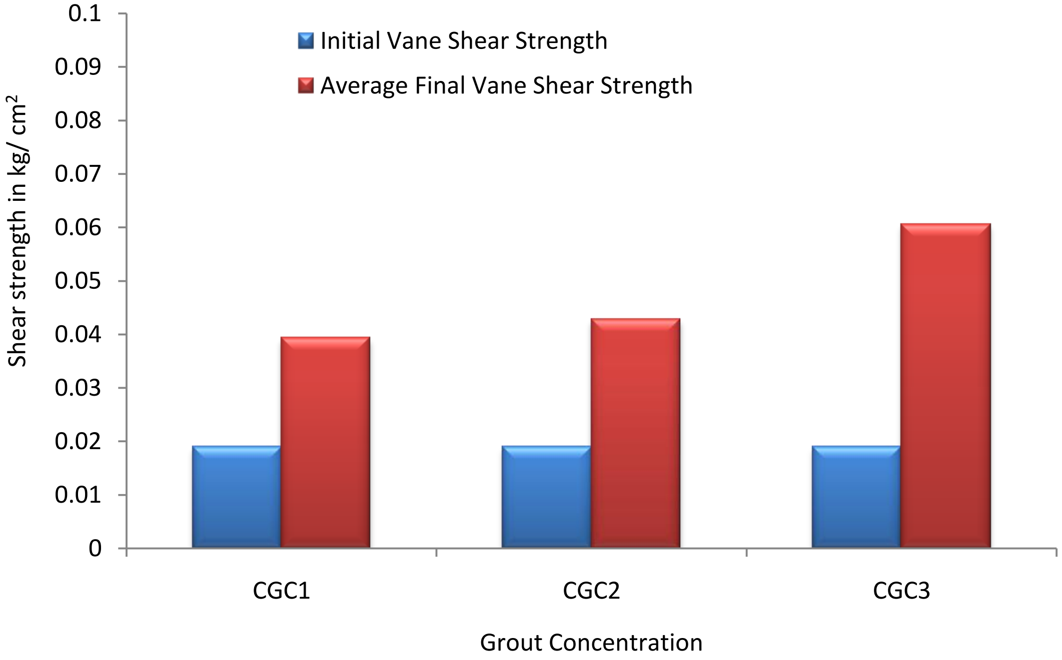


Fig. 4.39 Comparison of vane shear strength – Effect of grout concentration

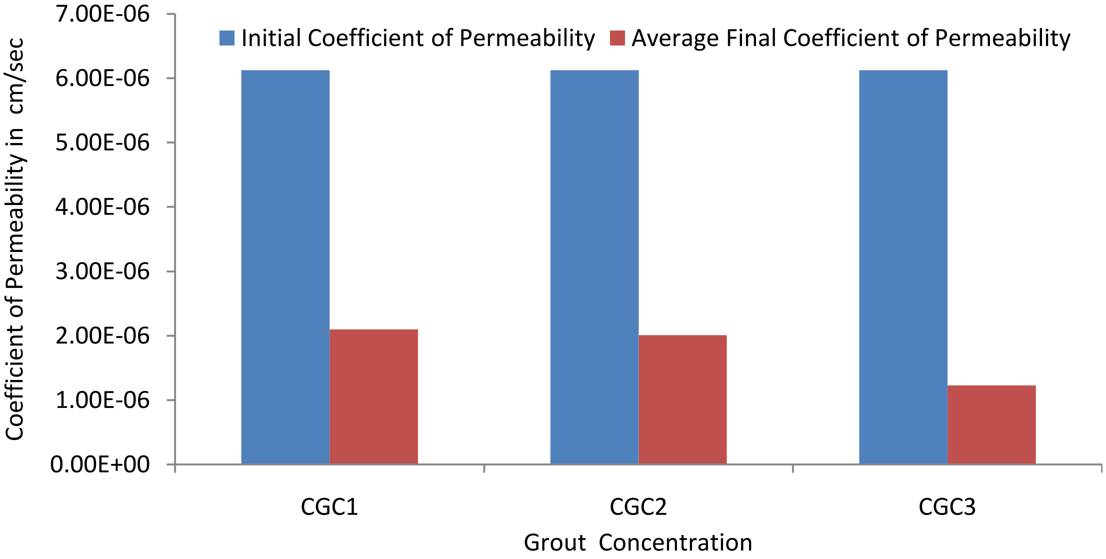


Fig. 4.40 Comparison of coefficient of permeability – Effect of grout concentration

Discussion: As the concentration of sodium silicate is increased in the cathode compartment its viscosity increases. Although this increase in viscosity reduces the flow rate of the solution, it in turn increases the quantity of sodium silicate available for reaction with calcium chloride thereby increasing the UCS due to the gelation of calcium silicate as is observed.

4.6.2.3 Effect of Experimental Duration

- **Closed Reactor – Experimental Duration 1 (CED 1)**

Analysis: CED 1 was similar to CSC 5. The results are as discussed for CSC 5.

- **Closed Reactor – Experimental Duration 2 (CED 2)**

Analysis: In this experiment, duration of testing was 15 days instead of 10 days. Figure 4.41 shows the comparison of initial and final vane shear strength of soil at constant water content along the length of the sample. The vane shear strength increased from 0.018 kg/cm^2 to 0.07 kg/cm^2.

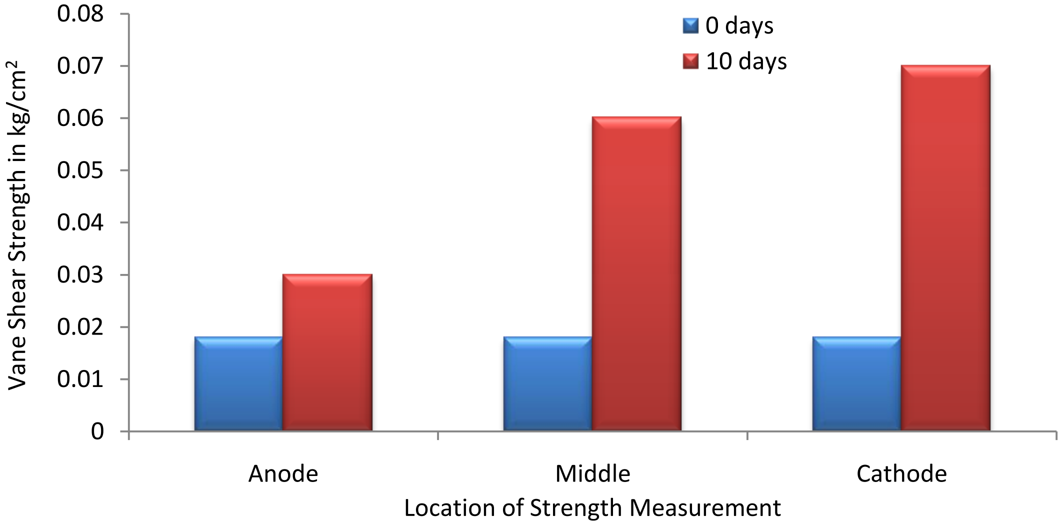


Fig. 4.41 Comparison of initial and final vane shear strength of soil at different locations (CED 2)

- **Closed Reactor – Experimental Duration 3 (CED 3)**

Analysis: In this experiment duration of testing was 20 days. The vane shear strength increased from initial value of 0.018 kg/cm^2 to 0.078 kg/cm^2 (Fig. 4.42) near cathode to 0.037 kg/cm^2 near the anode and to 0.065 kg/cm^2 in the middle section.

- **Closed Reactor – Experimental Duration 4 (CED 4)**

Analysis: Duration of testing in this experiment was 25 days. The vane shear strength increased from the initial value of 0.018 kg/cm^2 to 0.041 kg/cm^2 near anode. Vane shear strength observed at middle section and near the cathode was 0.068 kg/cm^2 and 0.087 kg/cm^2 respectively (Fig. 4.43).

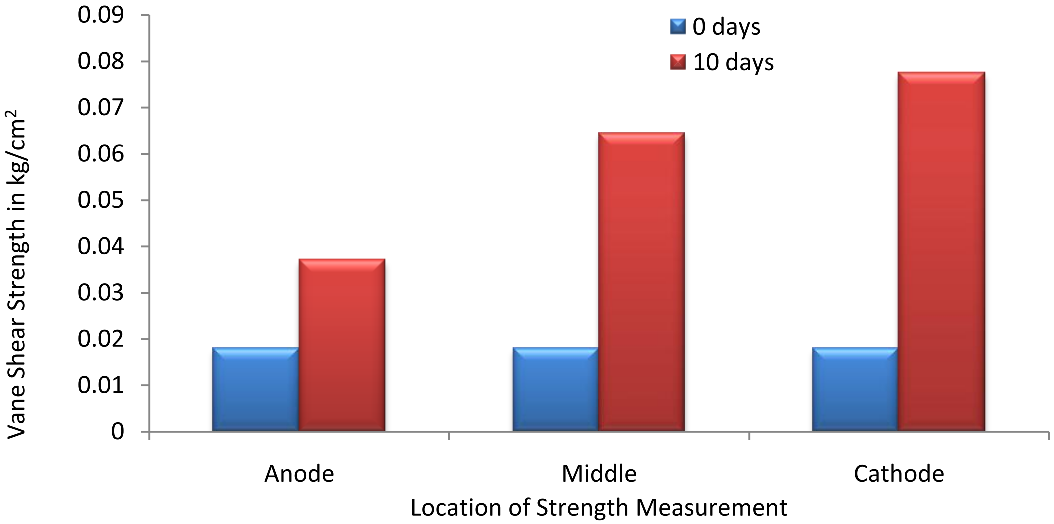


Fig. 4.42 Comparison of initial and final vane shear strength of soil at different locations (CED 3)

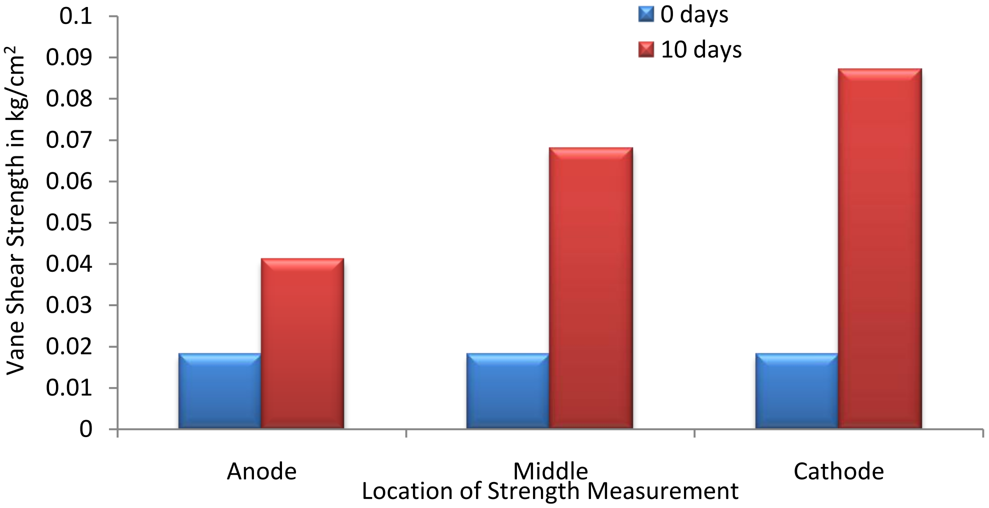


Fig. 4.43 Comparison of initial and final vane shear strength of soil at different locations (CED 4)

- **Closed Reactor – Experimental Duration 5 (CED 5)**

Analysis: In this experiment duration of testing was 30 days. Figure 4.44 shows the comparison of initial and final vane shear strength of soil at constant water content along the length of the sample. The vane shear strength increased from its initial value of 0.018 kg/cm^2 to 0.092 kg/cm^2 near the cathode, to 0.048 kg/cm^2 near anode and 0.048 kg/cm^2 at the middle section.

To study the effect of experimental duration on electrokinetic experiment, five experiments are performed during the course of study; i.e. 10, 15, 20, 25 and 30 days. Figures 4.45 and 4.46 show the comparative plot of vane shear strength and permeability for all the soil pre and post electrokinetic grouting of effect of experimental duration. The maximum vane shear strength was observed at 30 days (CED 5) i.e. 0.07 kg/cm^2. The minimum vane shear strength was obtained at 10 days (CED 1) i.e. 0.038 kg/cm^2. The vane shear strength was increased as increase in the days. The maximum decrease in the permeability was observed at 35 days (CED 5) i.e. 1.23E-06 cm/sec. The minimum decrease in permeability was observed at 10 days (CED 1) i.e. 2.45E-06 cm/sec.

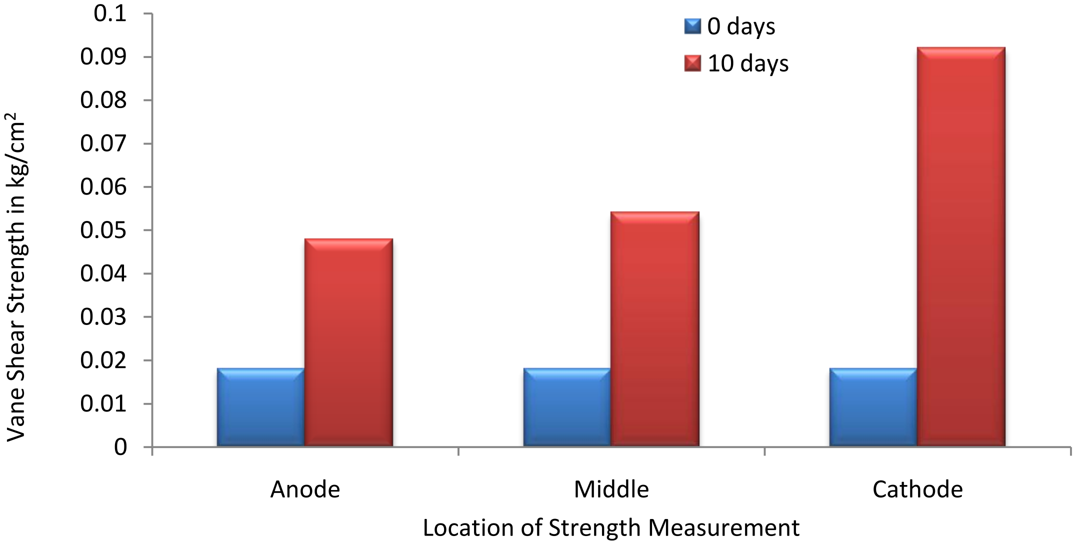


Fig. 4.44 Comparison of initial and final vane shear strength of soil at different locations (CED 5)

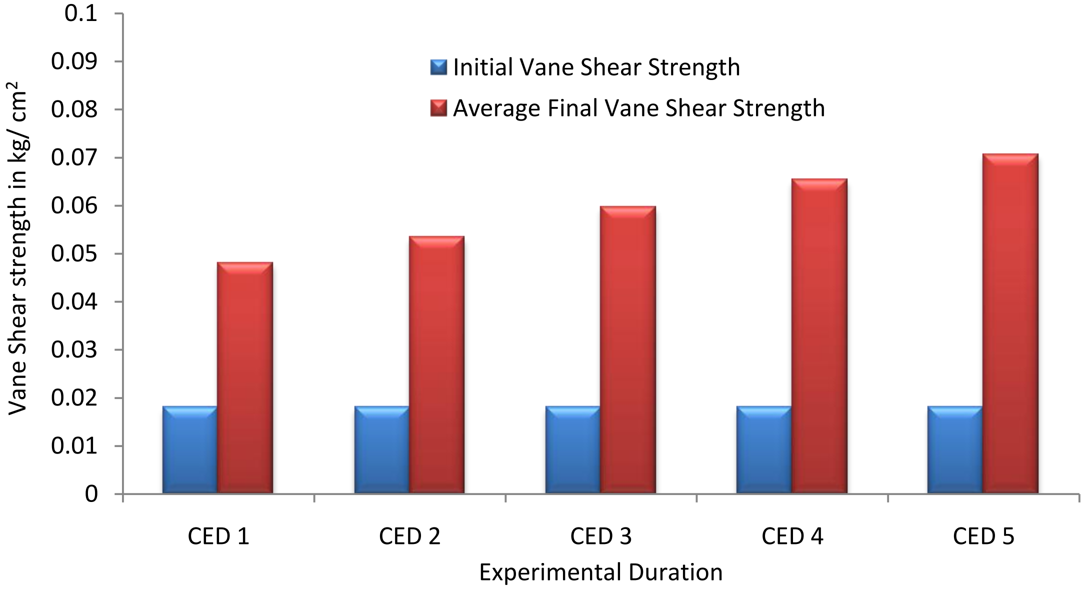


Fig. 4.45 Comparison of vane shear strength - Effect of experimental duration

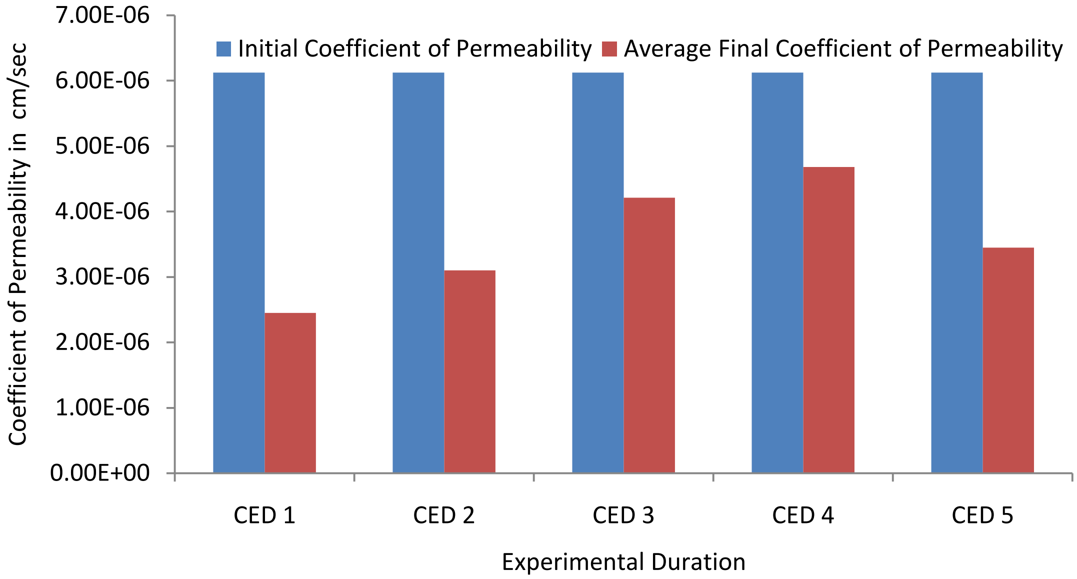


Fig. 4.46 Comparison of coefficient of permeability - Effect of experimental duration

Discussion: As the experimental duration is increase the grout has more time to penetrate into the soil. With longer application of DC supply alongwith the application of the grout solution, there is an increase in the hydration of the cation, which causes more absorbed water, alongwith the cation, to migration towards the cathode. The water content thus decreases with the increasing distance from the anode. Also longer duration of supply causes the Ca^{2+} to exchange with any available Na^{+} from the surface of the clay particles, making the double layer of clayey soils thinner, resulting in dense clay particles and thus increasing its shear strength. An increase in shear strength of soil can also be related to precipitation in the soil. This explain the higher improvement in clayey soils as compared to sandy soils even though the grout travels easily in larger pore sizes.

4.6.2.4 Effect of Electrode Spacing

- **Closed Reactor – Electrode Spacing 1 (CES 1)**

Analysis: CES 1 was similar to CSC 5 and the results are as discussed for CSC 5.

- **Closed Reactor – Electrode Spacing 2 (CES 2)**

Analysis: Figure 4.47 shows the comparison of initial and final vane shear strength of soil at different locations. The vane shear strength increased from 0.018 kg/cm^2 to 0.046 kg/cm^2 near the cathode. The minimum vane shear strength was observed near anode at 0.041 kg/cm^2.

- **Closed Reactor – Electrode Spacing 3 (CES 3)**

Analysis: Figure 4.48 show the comparison of vane shear strength with virgin soil. The initial vane shear strength observed was 0.018 kg/cm^2. Increase in vane shear strength observed near anode, middle section and near cathode was 0.031 kg/cm^2, 0.0438 kg/cm^2 and 0.044 kg/cm^2 respectively.

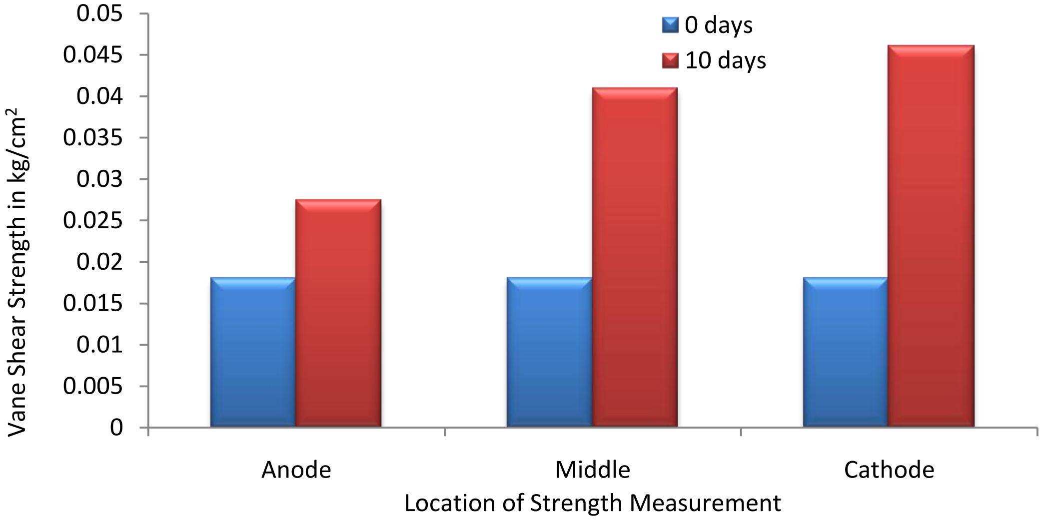


Fig. 4.47 Comparison of initial and final vane shear strength of soil at different locations (CES 2)

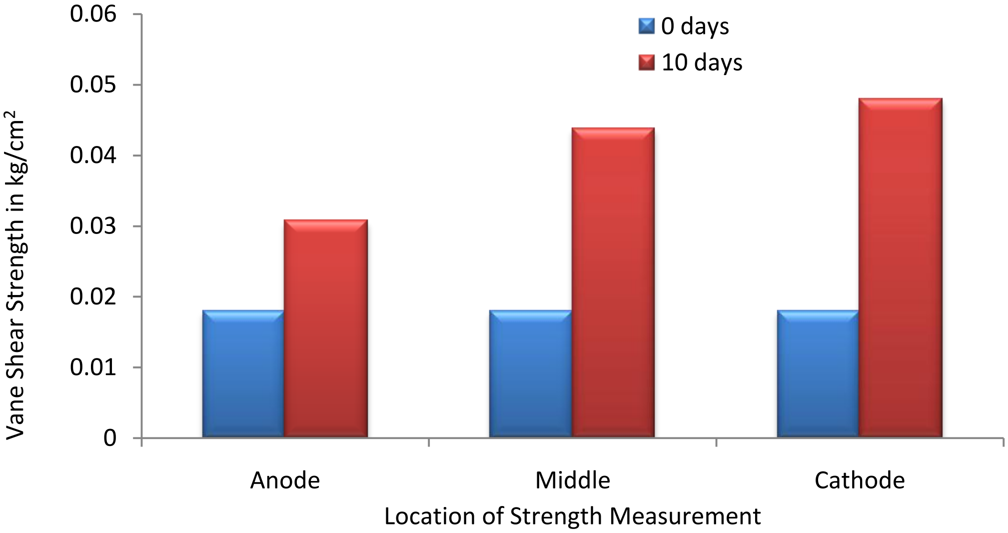


Fig. 4.48 Comparison of initial and final vane shear strength of soil at different locations (CES 3)

- **Closed Reactor – Electrode Spacing 4 (CES 4)**

Analysis: Figure 4.49 show the comparison of vane shear strength with initial strength of soil. The average strength increase observed over all three sections was 116.67%. Maximum vane shear strength was observed near the cathode i.e. 0.12 kg/cm^2 and the minimum vane shear strength was observed near anode i.e. 0.061 kg/cm^2.

To study the effect of electrode spacing on electrokinetic experiment, four experiments are performed during the course of study; i.e. electrode spacing = 34.5 cm, 45.72 cm, 68.58 cm, 91.44 cm for 5.08 cm diameter of reactor. The maximum vane shear strength was observed in ES 1 compared to other three electrodes spacing as shown in Fig. 4.50. The maximum increase in vane shear strength was 0.048 kg/cm^2 (166.67%). The minimum increase in vane shear strength for ES 3 was observed 0.038 kg/cm^2 (122.22%). Figure 4.51 shows that permeability was decreased with decrease in electrode spacing in Soil 5. The maximum decrease in permeability was found in ES1 i.e. 2.45E-06 cm/sec. The minimum decrease in permeability was observed in ES4 i.e. 4.68E-06 cm/sec.

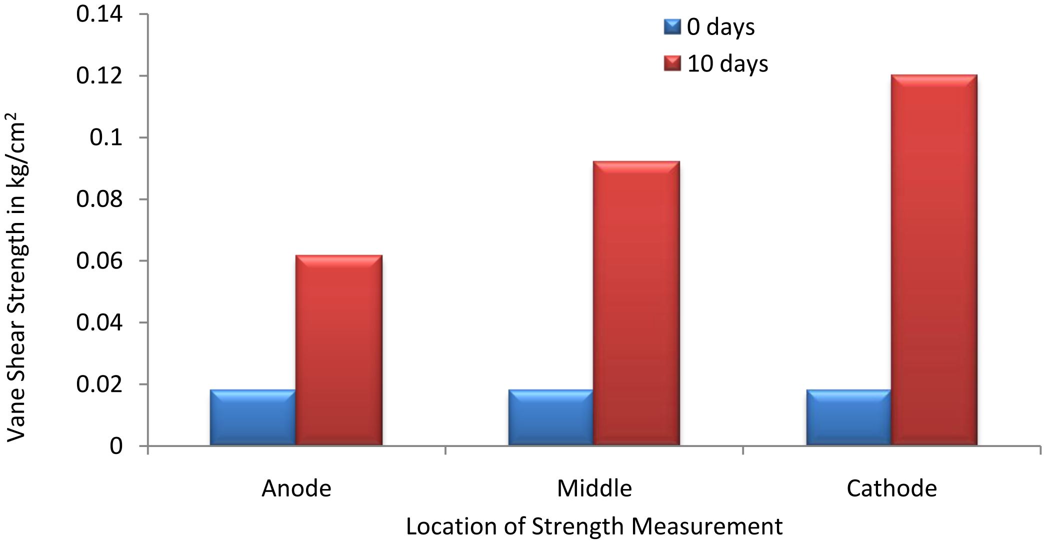


Fig. 4.49 Comparison of initial and final vane shear strength of soil at different locations (CES 4)

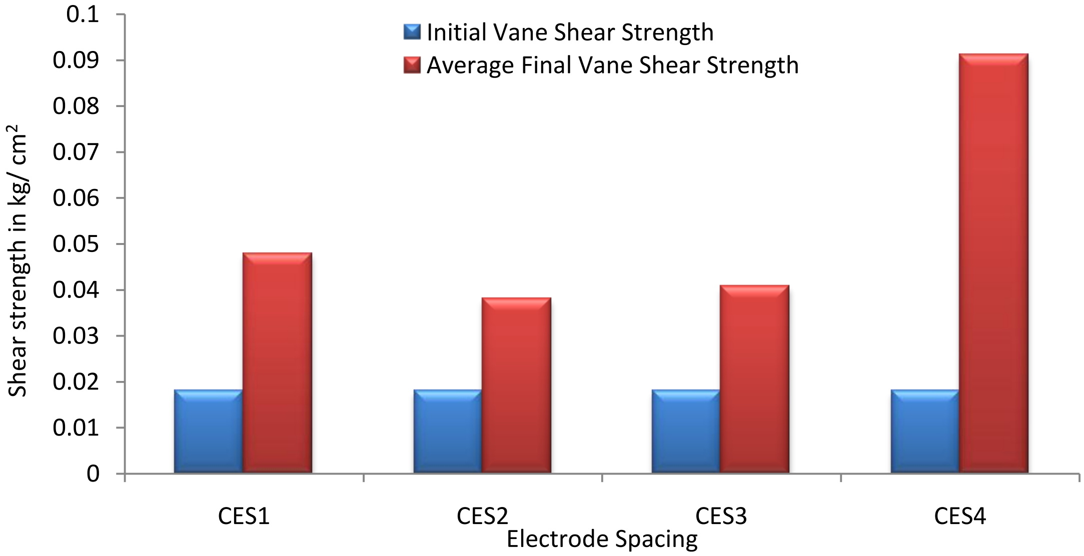


Fig. 4.50 Comparison of vane shear strength - Effect of electrode spacing

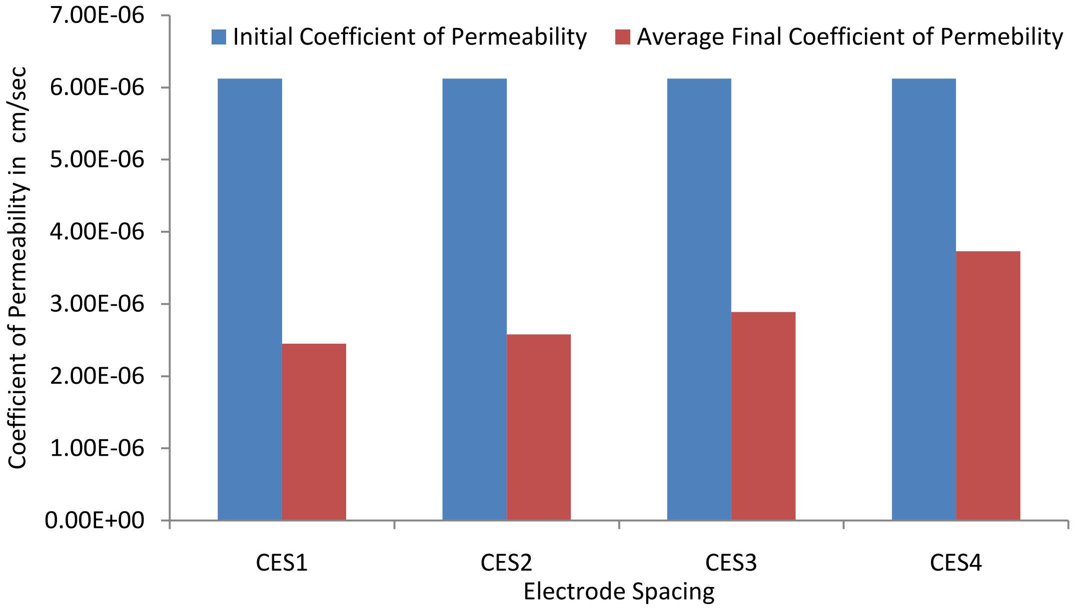


Fig. 4.51 Comparison of coefficient of permeability - Effect of electrode spacing

Discussion: As the electrode spacing is increased, it causes a higher voltage drop along the specimen, which provides lower electrical gradient for the grout components to dissociate and travel along with electro-osmotic movement. The drop in the electrical potential also reduces the hydrolysis reaction in turn affecting the electromigration of ions necessary for the formation of CSH gel along the length of the specimen. Increase in the electrode spacing need to be considered form the field point of view since a similar voltage gradient in the field would result in application of higher voltage. Therefore, special attention should be paid when designing the total electric voltage and the capacity of electric current before deciding the electrode arrangement as well as spacing on the field.

CHAPTER 5

Electrokinetic Dewatering using Conductive Geotextiles

Electrokinetic Dewatering Using Conductive Geotextiles

Chapter Five

5.1 EXISTING GEOSYNTHETIC MATERIALS

Modern geosynthetics were first developed for the Dutch "Delta Project" during the 1950's following the catastrophic floods which occurred in the Netherlands in February 1953. The sudden demand for construction materials outstripped the available supply and new innovative solutions were developed, with woven geotextiles replacing granular filter materials and woven willow branch scour protection (John 1987). During the 1960's and 70's the use of geosynthetics in filtration, separation and drainage applications increased. Rhone-Poulenc produced their needle punched "Bidim" range of geosynthetics, and ICI produced their heat bonded "Terram" range (John 1987). Geosynthetic materials used for reinforcement in the form of strips, tapes, sheets and grids were introduced in the 1970's. The behaviour of a geosynthetic material is governed by either its structural configuration, i.e. how its filaments are aligned, or the properties of the materials from which it is composed.

5.2 ELECTRICALLY CONDUCTIVE MATERIALS

Geosynthetic materials can be made electrically conductive in a number of ways as discussed below.

5.2.1 Weft Insert Warp Knit (WIWK)/ Stitch Bonded

These geotextile production techniques offer an extremely large variety of possibilities of producing materials and composites with particular functions. WIWK technology utilises a combination of weaving and knitting: the weft fibers are inserted across the width of the machine, behind the needles. The needles then knit along the machine direction (warp) by forming and stitching loops. This technique allows a wide range of geometries to be created; load bearing fibers to be introduced without tight radius curves; and brittle or difficult to handle fibers to be utilised (Andersson et. al. 1994). These techniques can be used with brittle fibers such as glass and carbon fibers. The weft inserts can be introduced in two different ways: impaled structures with stitches piercing the insert yarns and non impaled structures with stitches around the insert yarns.

5.2.2 Intrinsically Doped Polymers

Doped polymers can be produced by electrical or chemical deposition, examples are polybithiophene, which can be n(+) reduction or p(-) oxidation doped. However, these organic conducting polymers are not particularly stable, and are quickly attacked by oxygen and water, a process in which the double bonds are attacked and the compound hydrolyzed (Nettleton 1996). Spun polypropylene is a relatively cheap material that has an electrical conductivity of 100 S/cm. However, this material is very brittle and would require supporting on some other material such as PET or Polymethylmethacrylate (Campbell 1994).

5.2.3 Carbon Filled Polymers

Carbon filled polymers are produced by the addition of conductive carbon black powder to conventional polymers. Conductive carbon black powder is a high structure (long carbon chains) very fine particulate powder formed from the controlled burning of hydrocarbons. Virtually all thermoplastics can be compounded with carbon black powder (Wright & Woodham 1989). As the concentration of carbon black powder added to the polymer base increases so the electrical conductivity increases until the polymer becomes conductive, as show schematically in Figure 5.1. When carbon black is added to a polymer the physical strength properties are generally reduced with the degree of loss being proportional to the concentration of carbon black added, the higher the concentration of carbon black the lower the strength. In these composites it is the carbon filler that conducts electricity and not the polymer. If carbon black is used as the filler then a loading of between 20% - 30% by weight will be required to produces a suitable conductive polymer (Jones et al 1996).

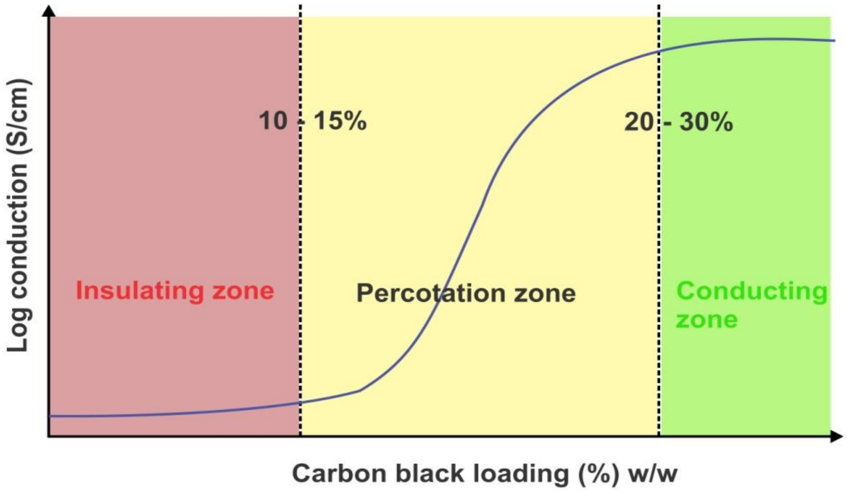


Fig. 5.1 Schematic of conductivity against carbon black loading for thermoplastic (Wright & Woodham 1989)

5.2.4 Carbon Fibers

Pure carbon fibers are more conductive than carbon filled polymers, but are more difficult to process. For example, carbon fiber rolled crystals are good stable conductors, but are stiff and brittle (Nettleton 1996). An additional possible problem with materials that use carbon as the conductive medium is that at large voltages carbon oxidizes to liberate carbon monoxide and dioxide at the anode, Equations 5.1 and 5.2 (Eastwood 1997):

$$C + 2H_2O \rightarrow CO_2 + 4H^+ + 4e^- \qquad E^{\theta}_{red} = 0.207V \qquad \text{Eqn. 5.1}$$

$$C + H_2O \rightarrow CO + 2H^+ + 2e^- \qquad E^{\theta}_{red} = 0.518V \qquad \text{Eqn. 5.2}$$

However, the addition of salt (NaCl) at the anode can prevent this. An additional problem is that in low pH (<4) environments carbon is oxidized, and if there is sufficient loss of carbon (40% percolation) gaps may from in the structure and electrons can no longer pass through the material and conductivity is lost (Nettleton 1996). These problems would also exist with a carbon filled polymer. However, at the voltages used for electro-osmosis this problem is unlikely to be significant.

5.2.5 Metallic Fibers

Fibers, metalized fibers or metal-coated fibers can be incorporated into the manufacturing process particularly if the material is formed by needle punching or weaving. Metal-coated fibers have a low electrical conductivity (10^{-6} - 10^{-1} S/cm) and are unsuitable for use in EKGs. However, the metal and metalized fibers are considered suitable, although their durability under anodic conditions is likely to be poor, unless they are noble metals.

5.3 EVOLUTION OF ELECTROKINETIC GEOSYNTHETICS (eKG)

An electrokinetic geosynthetic (eKG) may be defined as "A composite material which may provide filtration, drainage, reinforcement in addition to electrical conduction". (Jones et. al. 1996). The origins of the eKG began with groundbreaking research undertaken at the University of Newcastle upon Tyne during the early 1990's. The early work began by looking into the effects of combined drainage and reinforcement followed by the concept of making geosynthetics electrically conductive. Jones et al (1996) have reported a series of tests to study the effects of combining a drainage material with grid reinforcement in a clay soil (Heshmati, 1993). The results of this investigation demonstrated that the inclusion of a combined drainage / reinforcement geotextile reduced the effective angle of internal friction (ϕ') of the soil but caused a major increase in the effective cohesion (c'). Interestingly, Heshmati (1993) found that the materials providing drainage and reinforcement used separately produced greater improvement than the same materials providing combined drainage and reinforcement.

Jones et al (1996) introduced the concept of an electrically conductive geosynthetic material (eKG) and defined them as a range of geosynthetics, which, in addition to providing filtration, drainage and reinforcement can be enhanced by electrokinetic techniques for the transport of water and chemical species within fine grained low permeability soils, which are otherwise difficult or impossible to deal with. In addition transivity, sorption, wicking and hydrophobic tendencies may also be incorporated in the geosynthetic to enhance other properties. It is suggested that the eKG can take the form of a single material which is electrically conductive, or a composite material, in which at least one element is electrically conductive. Electrokinetic geosynthetics can be of the same basic form as present day filter, drainage, separator and reinforcement materials, but offer sufficient electrical conductivity to allow the application of electrokinetic techniques. Jones et. al. (1996) undertook a series of laboratory studies to evaluate the use of conductive geotextiles as electrodes in electro-osmotic consolidation and reinforced soil. The types of geosynthetics used included needle punched geotextiles with a 1 mm diameter copper wire inserted into the geotextile to make it electrically conductive, fiber (carbon) needle punched material and modified polyester reinforcing tape. The latter was made electrically conductive by the addition of a metal stringer aligned parallel to the polyester reinforcing elements. The results of the tests were favourable and indicated that the eKG behaved equivalent to a conventional copper electrode. In the reinforced soil tests the eKG electrode was used as an anode, with the cathode formed from a needle punched eKG. The results of pullout tests showed an increase in reinforcement bond of up to 211 % and increases in shear strength of up to 200% compared to the values obtained when the geosynthetics were not electrically conductive.

The laboratory experiments showed that the eKG electrodes were as good as or better than the copper disk. It was also found that the electrical interface resistance for the eKGs was higher than for the copper disk electrode. This was to be expected, as the conducting element of the eKG did not make direct contact with the soil but only indirectly through the pore fluid. The eKG electrodes were found to function as well as copper electrodes in laboratory consolidation trials with better durability in both normal and reverse polarity electro-osmotic consolidation. Nettleton et. al. (1998) continued the work presented by Jones et. al. (1996) and Hamir (1997) and suggested that a band drain type electrode would be the most suitable configuration to fulfill all of the electrode requirements associated with consolidation, bioremediation and moisture control in embankments. They suggested that a band drain can be made to act as a local distributor of electrical current by incorporation of carbon black fillers into the base polymer for either the geotextile filter or the drainage component of the band drain. Due to the electrical current requirements for electrokinetic treatment in commonly encountered soils a stringer was also required to conduct and distribute the bulk of the current through the band drain. The stringer could take the form of a metallic wire coated with a conductive polymer to prevent corrosion due to electrolysis (Nettleton 1996), which seems somewhat misleading in the sense that the coating of metallic wire with a conductive polymer will not prevent corrosion but will significantly reduce its rate of corrosion.

5.4 AIMS

The treatment of soft soils for infrastructure development as well as treatment and disposal of waste slurry materials is one of the most problematic issues affecting both developed and developing countries worldwide. Increasing environmental and economic pressures indicates a demand for more effective means of dewatering these sites along with an effective method for safe disposal of waste and/or reutilization at a later stage.

- The scope of this work is to weave a cost effective conductive geotextile as a viable technology. This technology has wide range of application in different genre of works beginning with dewatering applications for waste slurries, tailings, flyash ponds, to consolidation and/or dewatering of soft deep seated soil layers, to maintenance of lawns in large stadiums right upto irrigation and dewatering of lawns.

- Prove the reproducibility of the eK laboratory testing by conducting several replicate eK dewatering tests on waste slurry.
- Prove the reproducibility of the eK laboratory testing by conducting several replicate eK dewatering tests on soft soils along with comparison with gravity flow of water and atmospheric drying.
- Propose different means of applying eKG technology in practice in order to achieve safe and economic waste disposal and allow for the potential reuse of any of the waste components, particularly water.
- Reduce volume, by increasing dry solids content and disposal costs.

5.5 EXPERIMENTAL DEVELOPMENT AND MEASUREMENTS

5.5.1 Open Dewatering Reactors

Three laboratory scale reactors of size 26.5 cm x 20 cm x 20.5 cm were prepared using 9 mm waterproof plywood. Each consisted of a filter chamber provided at a distance of 1.5 cm from the bottom using an acrylic sheet as a separator for allowing free flow of water during the process. Standard quality filter paper was placed over this partition to restrict the flow of soil paste and soil particles into the filter chamber which was filled with 4.75 mm passing and 2mm retained coarse sand. Before using the reactor for experiments, they were checked for water tightness. Proper remedial measures were taken to avoid leakage, if any. Conductive geotextile was placed on the acrylic sheet to act as cathode with a carbon electrode being place at a distance of 13 cm from the bottom to act as an anode after the mould was filled with soil at its liquid limit. The electrodes were then connected using standard flexible copper wire to an AC-DC convertor unit. Figure 5.2 shows the schematic diagram of the dewatering setup.

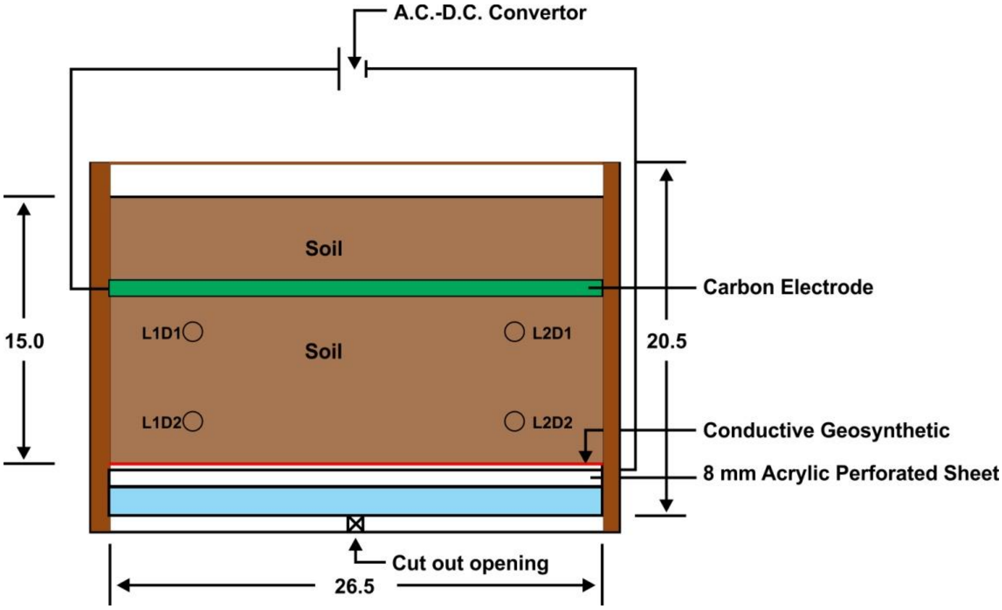


Fig 5.2 Schematic Diagram of Dewatering Setup

5.5.2 Conductive Geotextiles

5.5.2.1 Woven Conductive Geotextiles

The material used herein were 1.5d 44 mm polyester staples (Fig. 5.3), which were first processed on a miniature card machine (Fig. 5.4) to obtain a suitable fiber of 0.14 hank, also called as slubber. The slubber so obtained was fitted to a speed frame (Fig. 5.5 and 5.6) to obtain a roving material having hank value of 1.5. Copper wire (Fig. 5.7) was used for preparation of conductive textile. Figure 5.8 shows passage of filament for inserting twist wrap yarn on miniature ring frame. Subsequently the roving material was fitted to a miniature ring frame (Fig. 5.9). The draft and twist were set on a ring pen 20 and 20, to successively obtain the yarn count of 20s and twist per unit length of near about 20 (Fig. 5.10). The material so obtained referred hereon as copper yarn was then woven on a handloom to prepare the conductive geotextile. Steel filament (Fig. 5.11) was also used on the handloom to produce fabric in combination with other yarns, the details of which are mentioned in Table 5.1 A and B.

Fig. 5.3 Polyester Staple Fibers

Fig. 5.4 Miniature Card Machine

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Fig. 5.5 Speed Frame Machine

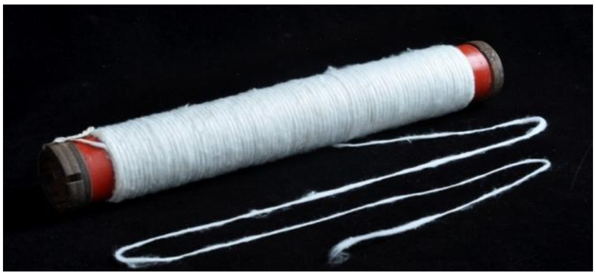


Fig. 5.6 Roving Bobbin

Fig. 5.7 Copper Wire

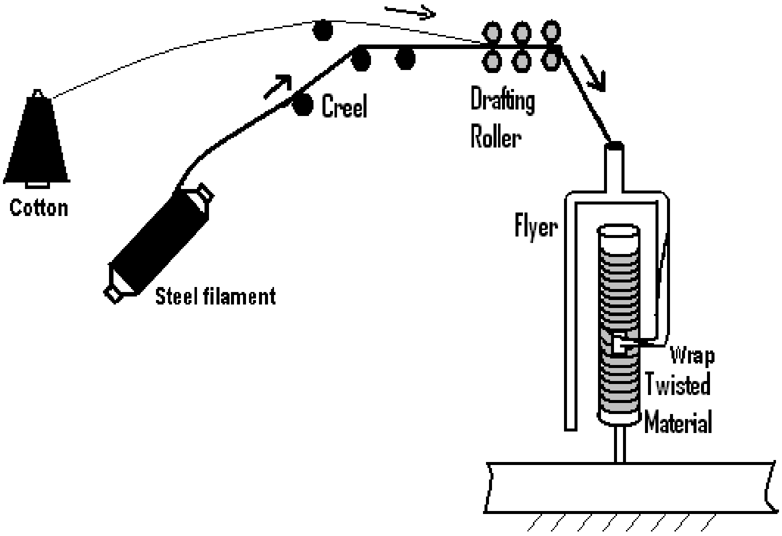


Fig. 5.8 Passage of filament for inserting twist/ wrap yarn on Miniature Ring Frame

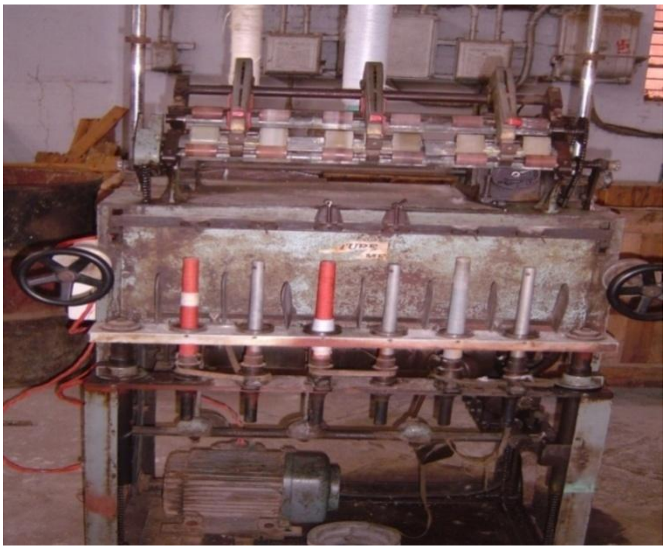


Fig. 5.9 Miniature Ring Frame

Fig. 5.10 Copper wire wrapped on polyester

Fig. 5.11 Steel yarn

Table 5.1A Weaving details of conductive woven geotextiles

Code	CGS 1	CGS 2	CGS 3	CGS 4	CGS 5	CGS 6
Machine Specification	HS= 2, RC = 36’s, FW = 8.66”	HS=2, RC=36’s, FW = 8.66”	HS=2, RC=36’s, FW = 2.67”	HS=2, RC=36’s, FW = 8.66”	HS=2, RC=36’s, FW = 8.66”	HS=2, RC=36’s, FW = 8.66”
Sample Specification	CuY x CuY	CuY x SF, 160.97x210.7 tex.	PPY&SF x PPY&SF 44.3x210.7 tex	PPY x SF 85.5x210.7tex.	CY&SF x CY&SF 44.3x210.7 tex	CY x SF 44.3x210.7 tex
Number of Filaments	Wa38 x Wr26	Wa40 x Wr16	Wa42 x Wr32 PR = 6c, 2 fil.	Wa38 x Wr26	Wa0 x Wr28 PR= 90c, 4 fil.	Wa36 x Wr40

PPY = Polyester Yarn, SF = Steel Filament, CuY = Copper Yarn, CY = Cotton Yarn, HS = Heald Shaft, FC = Reed Count, PR = Pattern Repeat

Table 5.1 B Different Types of Woven Conductive Geotextiles

CGS 1 **CGS 2** **CGS 3**

CGS 4 **CGS 5** **CGS 6**

- **Handloom Weaving:** Conversion of yarns to fabric can be brought about by various ways namely weaving, knitting, combination of both and other special techniques. Fibers can be directly compressed to fabric form by non-woven techniques. Of the above mentioned methods, weaving and knitting are very popular. Weaving can be accomplished by hand weaving or on power weaving machines. Handlooms are used with unlimited designing facilities in terms of "Weave repeat " that is interlacement pattern between two sets of yarns – warp yarn (running length wise) and weft yarn (running width wise). The simplest design "one up and one down" plain weave is shown diagrammatically (Fig. 5.12) along with interlacement pattern. Figure 5.13 shows a sketch of plain handloom. During fabric manufacturing on Handloom, the weaver alternatively lifts heald shaft 1 and 2, through the foot paddle forming an open space through which weft yarn was passed across the width of the sample. The required pattern of "conductive yarns" was obtained by drawing them through heald eye and reed. Fig. 5.14 depicts weaving on Handloom.

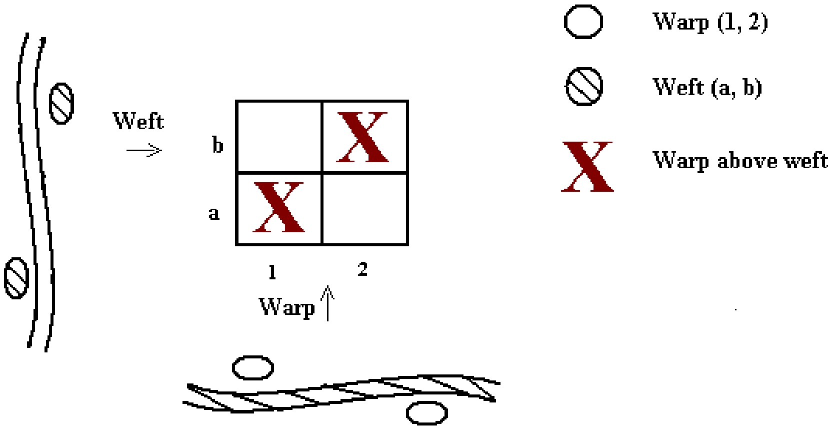


Fig. 5.12 Plain Weave along with interlacement pattern

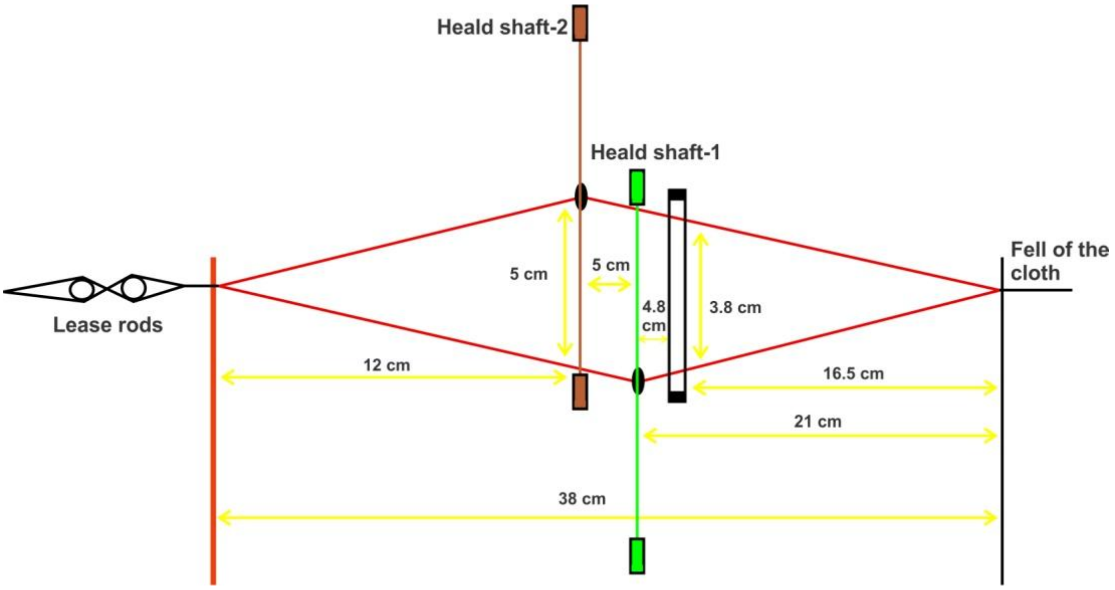


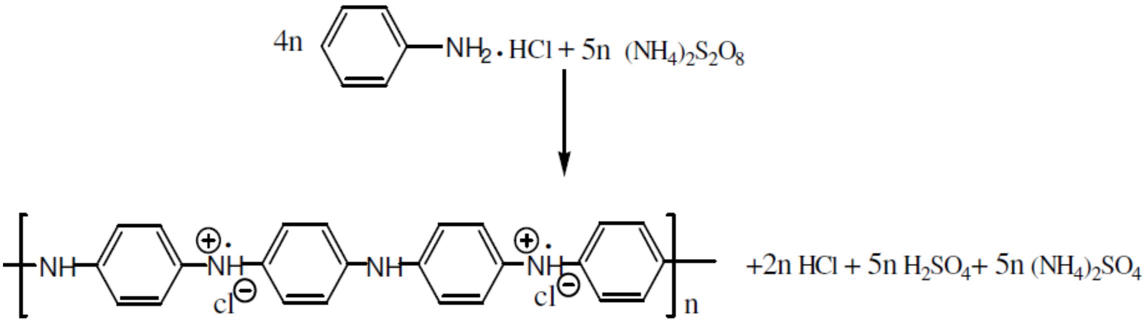
Fig. 5.13 Line Diagram for Plain Handloom.

Fig. 5.14 Weaving Process on Handloom

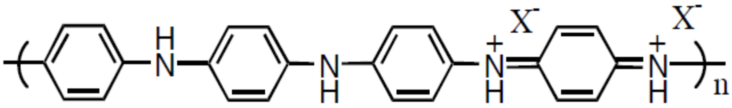
5.5.2.2 Conductive Coated Nonwoven Geotextiles

To prepare the conductive coating, 13.2 mL (0.2) of aniline was dissolved in 150 mL of 2M HCl and on the other hand 7 gm (0.1M) ammonium persulfate $(NH_4)_2S_2O_8$ was dissolved in 250 ml of water and then was added into the well stirred monomer solution over a period of 40 minutes. Polymerization was carried out at 0~5°C. The molar ratio of monomer to oxidant was selected 1:1. The solution was stirring continuously for 2h after complete addition of the oxidant. The green dark powder obtained was filtered, washed with dilute HCl solution, followed by distilled water and methanol to remove impurities and unreacted monomer. Then the product was dried at 50-60°C. The obtained poly aniline was treated with a solution of ammonia (0.5M) for 4 hours at room temperature to convert it to emeraldine base, which was then filtered and washed thoroughly with distilled water and dried. Similarly poly o-toluidine was synthesized from 21.4 mL o-toluidine (0.2 mol) using ammonium persulfate as an oxidant in the molar ratio 1:1.

REACTION:



Poly aniline



Green, partially oxidized protonated Emeraldine Base (Conducting Form)

- **Method of Coating:** Conducting polymer EB and the binder nylon 6 were separately dissolved in formic acid (1% w/v). Both the solutions were mixed to obtain a homogeneous mixture which was further coated on the non woven geotextile material. The swatch was dried in an oven at 60°C overnight. After complete drying, this coated material was used it for electrokinetic dewatering application (Fig. 5.15(a)). Similarly EB and the binder polycarbonate were separately dissolved in formic acid (1% w/v) and dichloromethane (1% w/v) respectively (Fig. 5.15 (b)). Similarly Poly o-toluidine and the binder nylon 6 were separately dissolved in formic acid (1% w/v) (Fig. 5.15 (c)).

5.5.3 Setup and Conduction of Experiments

For this study, six different types of soil compositions as elaborated in Chapter 3, and single vermi compost were selected. All collected soils were air dried, pulverized and then oven dried at 105°C to remove moisture. Soil 1, Soil 2, Soil 3 and vermi compost were used directly as they were commercially procured soils. Soil 4, Soil 5 and Soil 6 were sieved through 425μ sieve before being used. Various factors such as effect of dewatering material, woven conductive geotextile, and use of conductive geotextile as a vertical geodrain were studied. To conduct electrokinetic dewatering experiments using conductive geotextile, soil mass was placed in the laboratory reactor at its liquid limit. A 10 mm diameter and 30 cm long scarifying carbon electrode as anode and conductive geotextile as cathode were used for the conduction of current (Fig. 5.2). The reactor had an arrangement to collect water at the bottom which was used to measure the volume of water flow as a cross check for water removal measured with respect to water content removal calculated using humidity and temperature transmitter (Fig. 5.16) and the tips used for measurement (Fig. 5.17). The test duration was 3 days for all experiments. Various readings such as ambient temperature, ambient humidity, current, humidity and strength were taken on daily basis at fixed time.

5.5.4 Observations

For all the experiments readings of current, current, ambient temperature, atmospheric humidity, humidity at surface and at depth and strength were being noted.

(a) (b) (c)

Fig 5.15 Geotextile Coated with (a) Emeraldine Base/Nylon 6 (b) Emeraldine Base/Polycarbonate (c) Poly(o-toluidine)/Nylon 6

Fig. 5.16 Humidity Meter

Fig. 5.17 Different Tip Attachments

5.6 EXPERIMENTAL SCHEDULE

For the experiments, six different soil compositions and vermi compost were selected, as shown in Table 5.2. This section of work is divided into 3 phases. Parameters adopted for the study are: Initial moisture content (%) and Final moisture content (%).

Table 5.2 Soil Code Name

Soil	Place of Procurement	Code Name
Flyash	Wanakbori	Soil 1
Bentonite	Bhavnagar	Soil 2
Kaolinite	Bhavnagar	Soil 3
Yellow Soil	Vadodara	Soil 4
Black cotton	Netrang	Soil 5
Yellow Soil	Sevasi	Soil 6
Vermi Compost	Nursery	VC

5.6.1 Phase I: Effect of Material Composition on eKG Dewatering

Five different types of soil composition and vermi compost were used to study and ascertain the effect of dewatering material composition. Applied voltage was kept same for all experiments. This phase consisted of six experiments, as mentioned below. For all the experiments, the conductive geotextile used was made up of polyester yarn in warp and steel filament in weft only. The readings for current, ambient temperature, atmospheric humidity, humidity at surface and depth and strength were noted periodically.

Experimental parameters

Type of Supply	Applied Voltage	Experimental Duration	Type of Geotextile
DC	15V	3 Days	Polyester yarn x Steel Filament

Experiment Designation	DM 1	DM 2	DM 3	DM 4	DM 5	DM 6
Dewatering Material	Soil 1	Soil 2	Soil 4	Soil 5	Soil 6	VC 1

5.6.2 Phase II: Effect of Type of Conductive Geotextile on eKG Dewatering

Extensive study was made to understand the effect of geotextile. Soil 6 was used for six different types of geotextiles. Applied voltage was kept same as Phase I. Extensive study was carried out to understand the effect of type of woven conductive geotextile on the percentage dewatering of the selected soil i.e. Soil 6. Different geotextiles were prepared by varying the weaving material and weave direction of the conductive material. The readings for current, ambient temperature, atmospheric humidity, humidity at surface and depth and strength were noted at fixed time intervals.

Experimental parameters

Type of Supply	Applied Voltage	Experimental Duration	Dewatering Material
DC	15V	3 Days	Soil 6

Experiment Designation	Type of Geotextile
GWT 1	Copper wrapped polyester yarn (CGS 1)
GWT 2	Copper yarn x Steel filament (CGS 2)
GWT 3	Polyester yarn & Steel filament x Polyester yarn & Steel filament (CGS 3)
GWT 4	Polyester yarn x Steel filament (CGS 4)
GWT 5	Cotton Yarn & Steel filament x Cotton yarn & Steel filament (CGS 5)
GWT 6	Cotton yarn x Steel filament (CGS 6)

5.6.3 Phase III: eKG as Conductive Vertical Geodrain for Dewatering

To ascertain the effect of Vertical geodrain, an experiment was conducted on Soil 3, in which applied voltage was kept same as Phase I. To ascertain the effect of conductive vertical geodrain, an experiment was conducted on Soil 3; details for which are given below. Applied voltage was kept same as the Phase I. The readings for current, ambient temperature, atmospheric humidity, humidity at surface and depth and vane shear strength were noted.

Experimental parameters

Type of Supply	Applied Voltage	Experimental Duration	Dewatering Material	Experimental Designation	Type of Geotextile
DC	15V	3 Days	Soil 3	VD1	Polyester yarn x Steel filament

5.6.4 Phase IV: Effect of Type of Conductive Coating on Nonwoven Geotextile

To study the effect of type of coating for conductive coated nonwoven geotextile, three experiments were performed on Soil 4. Three different conductive coated nonwoven geotextile were used. Voltage applied was kept same as Phase 1. To ascertain the effect of various conductive formulations used to coat the nonwoven geotextiles three experiments were conductive on Soil 4. The readings for current, ambient temperature, atmospheric humidity, humidity at surface and depth and vane shear strength were noted.

Experimental parameters

Type of Supply	Applied Voltage	Experimental Duration	Dewatering Material
DC	15V	3 Days	Soil 4

Experiment Designation	Form of Coating
CNWG 1	Emeraldine base/ nylon 6
CNWG 2	Poly (o-toluidine)/nylon 6
CNWG 3	Emeraldine base/ polycarbonate

5.6.5 Phase V: Effect of Type of Conductive Coating on Nonwoven Geotextile for Re-Run

To study the effectiveness of the coating for repeated use over a long duration a second run using the same coated textile after washing under running water was carried out. The applied voltage and all other parameters were kept constant as in Phase I. A single repeat run study was carried out to verify the stability of the conductive coating under repeated use after washing to simulate lashing of rain water under washout conditions. The details of the study carried out are shown below. Readings for current, ambient temperature, atmospheric humidity, humidity at surface and depth and vane shear strength were noted.

Experimental parameters

Type of Supply	Applied Voltage	Experimental Duration	Dewatering Material
DC	15V	3 Days	Soil 4

Experiment Designation	Type of Coating
GR 1	Emeraldine base/ polycarbonate
GR 1-1	Emeraldine base/ polycarbonate
GR 2	Poly (o-toluidine)/nylon 6
GR 2-1	Poly (o-toluidine)/nylon 6

5.6.6 Phase VI: Effect of Material Composition on Conductive Coating for Dewatering

Two different soils were used to study and ascertain the effect of dewatering material composition on conductive coated non woven geotextiles. Applied voltage was kept same for all experiments. Two different soils were used to study and ascertain the effect of dewatering material composition on conductive coated non woven geotextiles. Applied voltage was kept same for all experiments.

Experimental parameters

Type of Supply	Applied Voltage	Experimental Duration	Conductive Coating
DC	15V	3 Days	Emeraldine base/nylon 6

Experiment Designation	Type of Soil
SCC 1	Soil 4
SCC 2	Soil 6

5.7 EXPERIMENTAL RESULTS AND DISCUSSION

For the experiments of dewatering five types of soils and one vermi compost was used. Geotechnical properties of the virgin soil were determined using standard methods as prescribed in relevant IS codes mentioned in IS 2720. These properties are summarized below in Table 5.3.

Table 5.3 Properties of Soils for Conductive Geotextile

Type of Soil	Place of Procurement	Code Name	Liquid Limit (%)	Plastic Limit (%)	IS Classification
Flyash	Wanakbori	Soil 1	45.0	-	-
Bentonite	Bhavnagar	Soil 2	153	-	CH
Kaolinite	Bhavnagar	Soil 3	73.8	33.2	CH
Yellow	Vadodara	Soil 4	30	NP	ML
Black Cotton	Netrang	Soil 5	54	25	CH
Yellow Clayey	Sevasi	Soil 6	32	20	CL

5.7.1 Effect of Material Composition on eKG Dewatering

Analysis: Five different soil compositions along with vermi compost were used for this phase. Fig. 5.18 shows relative humidity profile versus time for DM 1 (Soil 1). It is noted that the humidity reduced with increase in time. The maximum humidity was observed at L2-D2 (52%) whereas minimum humidity was observed at L1-D1 (44%). Fig. 5.19 shows the relative humidity profile versus time for DM 2 (Soil 3).

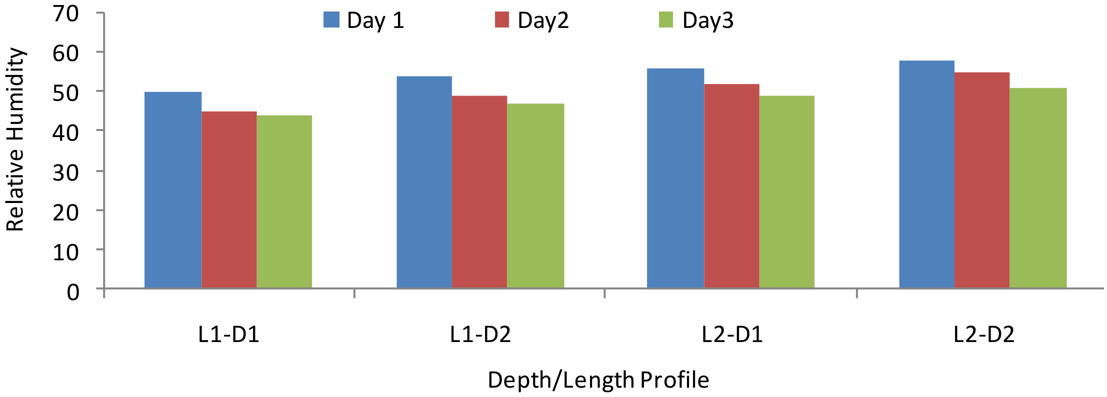


Fig. 5.18 Relative humidity profile versus time (DM 1)

The maximum humidity was observed at L2-D2 (66%) and minimum humidity was observed at L1-D1 (58%). Fig. 5.20 shows the relative humidity profile versus time for DM 3 (Soil 4). The maximum humidity was observed at L2-D2 (60%) and minimum humidity was observed at L1-D1 (54%). Fig. 5.21 shows the relative humidity profile versus time DM 4 (Soil 5). The maximum humidity was observed at L2-D1 (43%) and minimum humidity was observed at L1-D1 (31%). Fig. 5.22 shows the relative humidity profile versus time for DM 5 (Soil 6). The maximum humidity was observed at L2-D2 (52%) and minimum humidity was observed at L1-D1 (39%). Vermi compost was used to performed experiment DM 6. Fig. 5.23 shows the relative humidity profile versus time. The maximum humidity was observed similar at L1-D2, L2-D1 and L2-D2 (52%) and minimum humidity was observed at L1-D1 (52%).

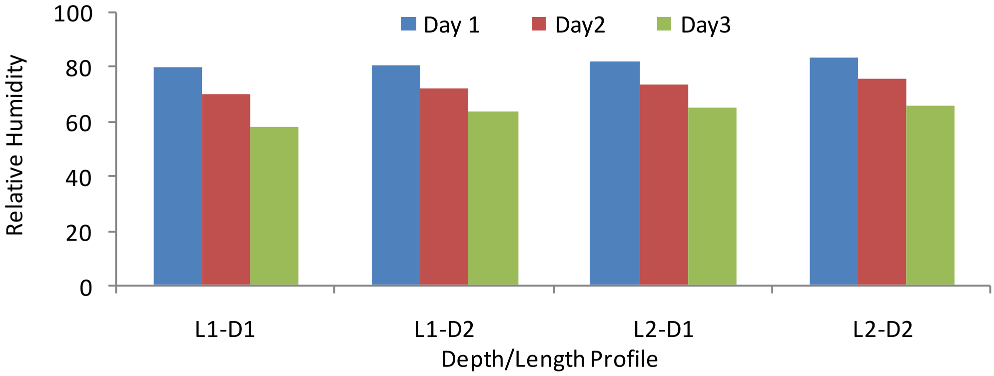


Fig. 5.19 Relative humidity profile versus time (DM 2)

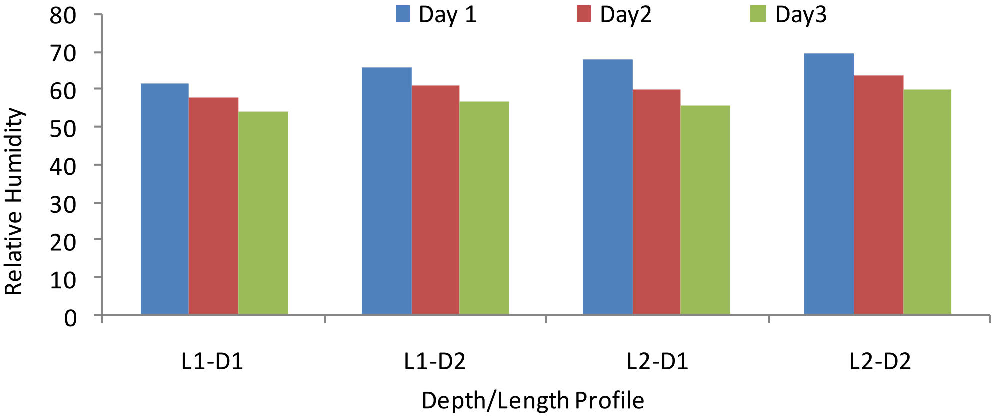


Fig. 5.20 Relative humidity profile versus time (DM 3)

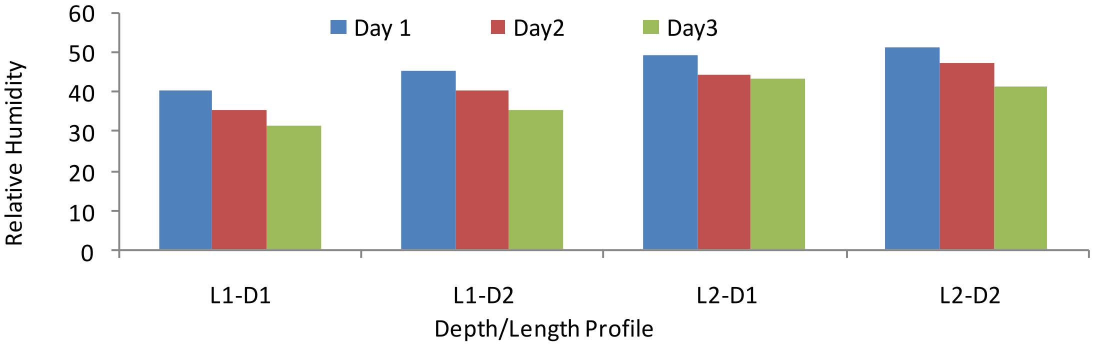


Fig. 5.21 Relative humidity profile versus time (DM 4)

The effect of EK treatment was further evaluated from the undrained shear strength and water content after treatment. Fig. 5.24 & 5.25 show the comparison of water content and percentage removal of water. For DM 1 the initial moisture content observed was 54.8 % and final moisture content was 50.64% showing a reduction of 7.59%. For DM 2 the moisture content decreased from the initial value of 153% to 146.23% as indicated by percentage water reduction in moisture content by 4.43%. For DM 3 as shown in Fig. 5.24 the moisture content decreased from 28% to 20.05%. And percentage water reduction in moisture content was noticeable (28.39%). For DM 4 the initial water content observed was 47.6%. The final water content was 41.56% and percentage water removal observed was 12.69%. The water content decreased from 33.27% to 21.38% showing a reduction of 35.73% in case of DM 5. In DM 6 the water content decreased from 0.56% to 12.21% with a total percentage water removal was 40.61%.

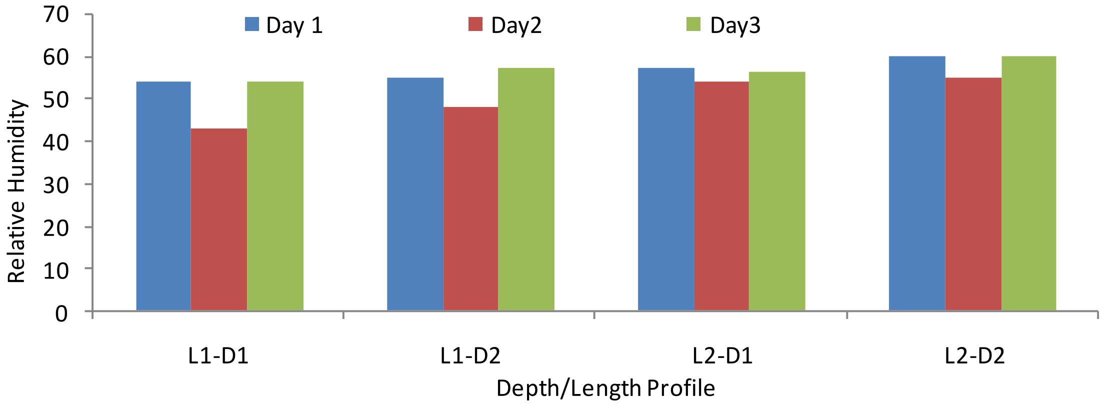


Fig. 5.22 Relative humidity profile versus time (DM 5)

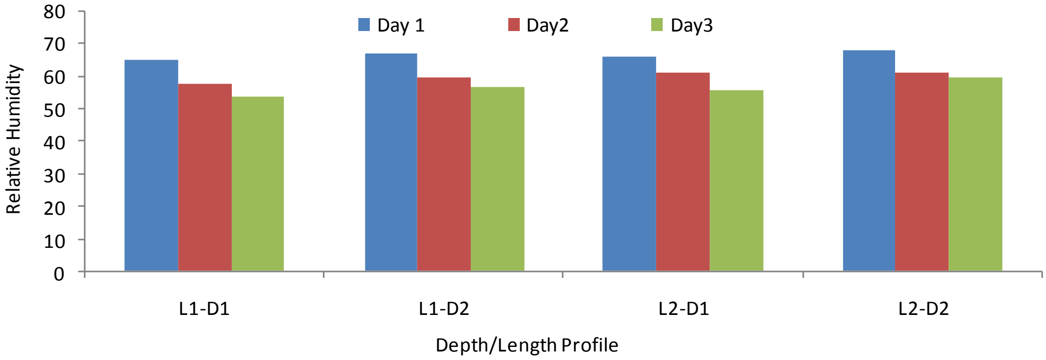


Fig. 5.23 Relative humidity profile versus time (DM 6)

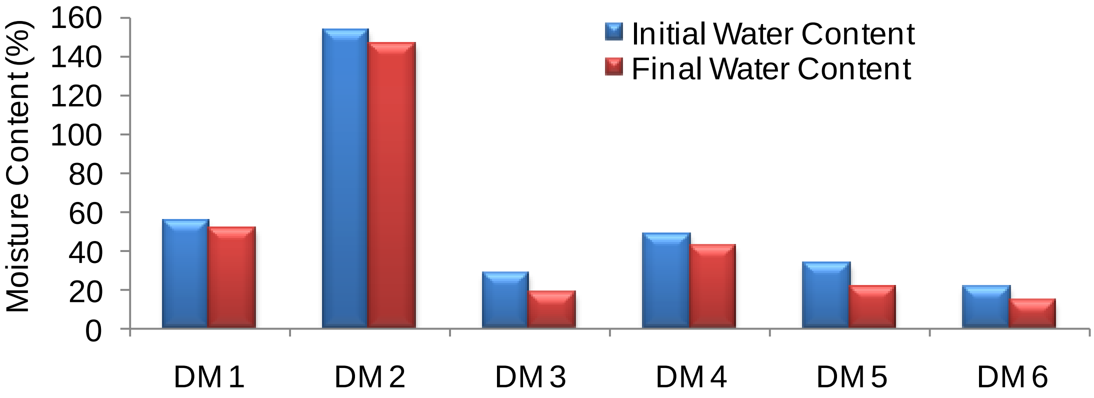


Fig. 5.24 Comparison of water content – Effect of dewatering material

Figure 5.26 shows that the soil shear strengths after electrokinetic testing at all locations was higher than those of the control samples. For DM 1, on passing current through the setup, the strength gradually increased showing a rapid rise between 6 and 30 hours followed by a gradual but significant increase throughout the experiment. The final strength noted was 0.063 kg/cm^2 at the end of 72 hours showing an overall of 60.15% increase in strength. For DM 2, on supplying current through the setup, showing rapid rise in strength between 0 and 6 hours and between 30 and 54 hours followed by gradual increase in strength upto 72 hours. The final strength observed was 0.058 kg/cm^2 at the end of 72 hours, showing an overall of 109.13% increase in strength. For DM 3, after applying current, the strength gradually increased showing a rapid rise between 30 to 72 hours. The final strength observed was 0.045 kg/cm^2 at the end of 72 hours showing an overall 136.84% increase in strength (Fig. 5.26).

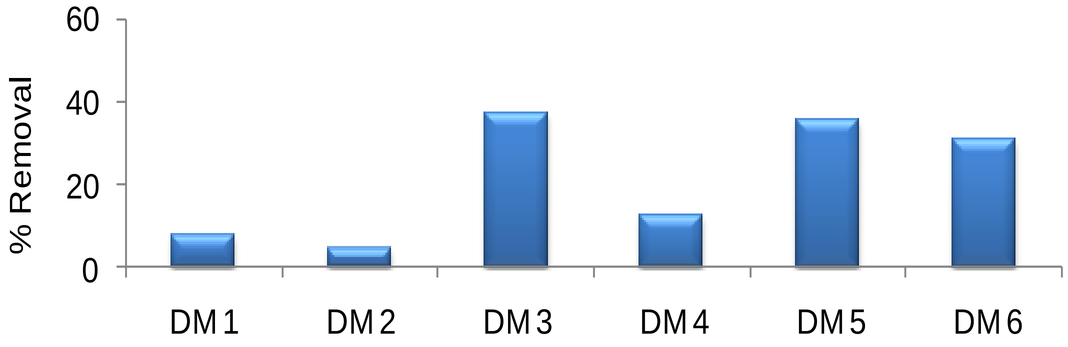


Fig. 5.25 Comparison of removal of water – Effect of dewatering material

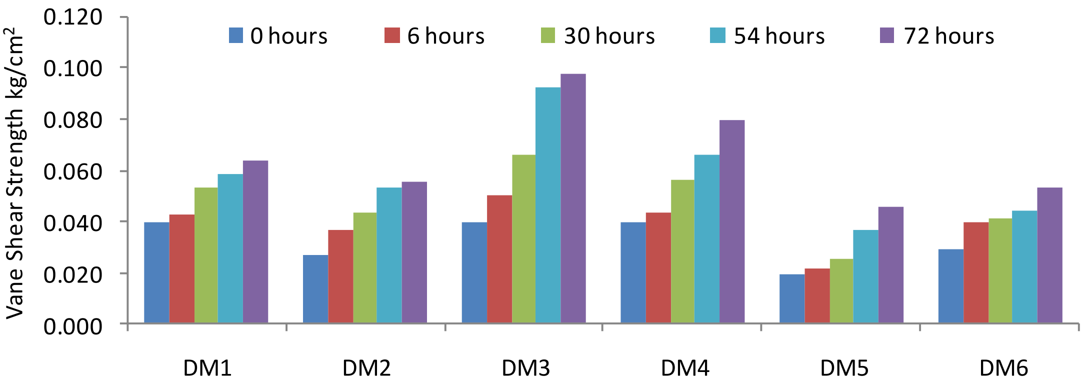


Fig. 5.26 Comparison of vane shear strength – Effect of dewatering material

For DM 4, the strength gradually increased showing a rapid rise between 6 and 30 hours followed by gradual but significant increase noted at 54 hours showing rapid rise between 54 and 72 hours. The final strength observed was 0.066 kg/cm^2 at the end of the experiment (102.5%). It demonstrated higher shear strength without significant decreases in water content. For DM 5, on an applying current, the strength gradual but significant increase was observed followed by a steep rise between 30 and 54 hours followed by a gradual increase. At the end of the experiment the strength was noted was 0.097 kg/cm^2 showing an overall 147.2% increase in strength. For DM 6, after supplying current, steep rise was noted between 0 and 6 hours and 54 and 72 hours showing gradually increase in the strength. At the 72 hours the final strength observed was 0.053 kg/cm^2 (82.7%).

Discussion: The removal of water from silty soil is much better since the water holding capacity of silty soil as compared to black cotton clayey soil is much less thereby offering reduced resistance to water movement under the same applicable voltage gradient. The removal percentage can be increased by increasing the voltage gradient rather than duration of test. The changes in shear strength and water content were more significant at the anode than at the cathode, which is consistent with the theory of electroosmotic consolidation. The non uniform shear strength increase due to electroosmosis in a soil could cause local differential settlements. The increase in shear strength is attributed to cementation bonding generated by electrokinetics at the cathode, which has not been reported previously in any of the literature. It is considered that the possible causes of this cementation could be selective sorption and ionic exchange of ionic species on clay particle surfaces and precipitation of amorphous compounds such as iron oxides and carbonates which can serve as cementing agents.

5.7.2 Effect of Type of Conductive Geotextile on eKG Dewatering

Analysis: This phase of work was carried out using Soil 6 only. Figure 5.27 shows the plot of relative humidity profile with time. For GWT 1 the maximum humidity was observed at section L2-D2 (51%) and minimum was observed at L1-D1 (44%). For GWT 2 the plot of relative humidity profile with time is shown in figure 5.28 The maximum humidity was observed at section L2-D2 (66%) and minimum was observed at L1-D1 (58%). For GWT 3, figure 5.29 shows the relative humidity profile with time plot. The maximum humidity was observed at section L2-D2 (60%) and minimum was observed at L1-D1 (54%).

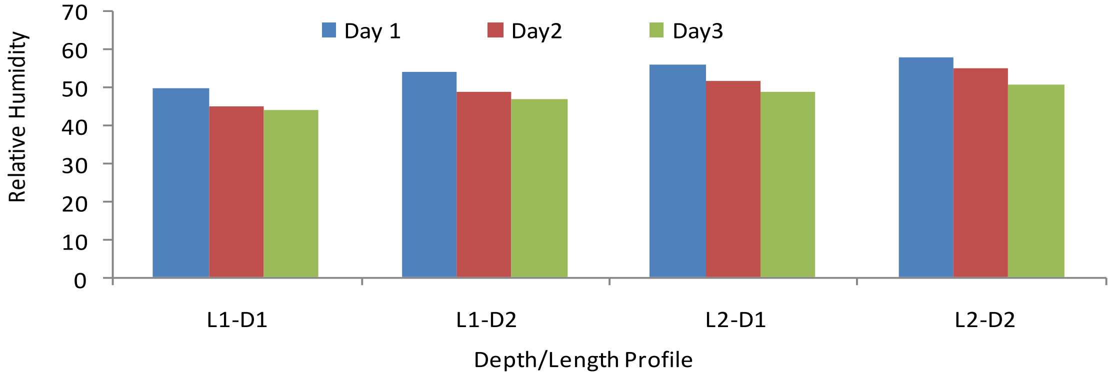


Fig. 5.27 Relative humidity profile versus time (GWT 1)

Figure 5.30 shows the relative humidity profile with time for GWT 4. The maximum humidity was observed at section L2-D1 (43%) and minimum was observed at L1-D1 (31%). For GWT 5, figure 5.31 shows the plot of relative humidity profile with time. The maximum humidity was observed at section L2-D2 (52%) and minimum was observed at L1-D1 (39%). For GWT 6, figure 5.32 shows plot of relative humidity profile with time. The maximum humidity was observed at section L2-D2 (53%) and minimum was observed at L1-D1 (51%).

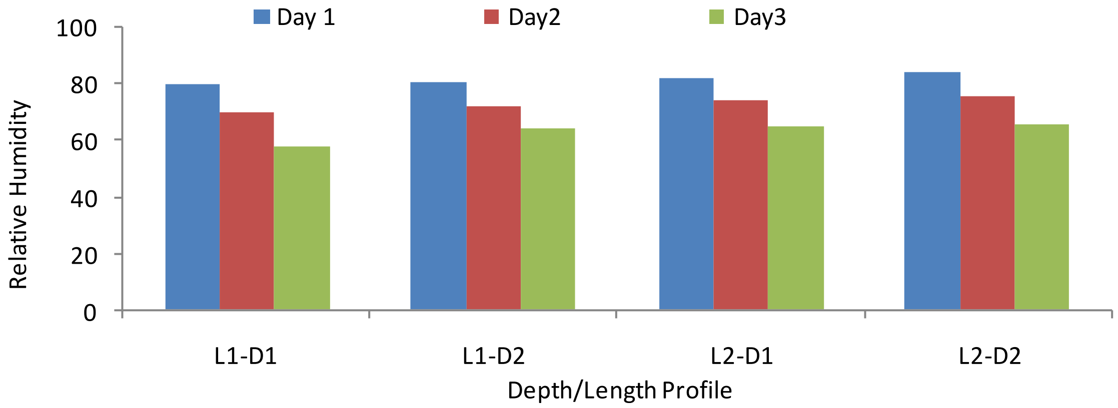


Fig. 5.28 Relative humidity profile versus time (GWT 2)

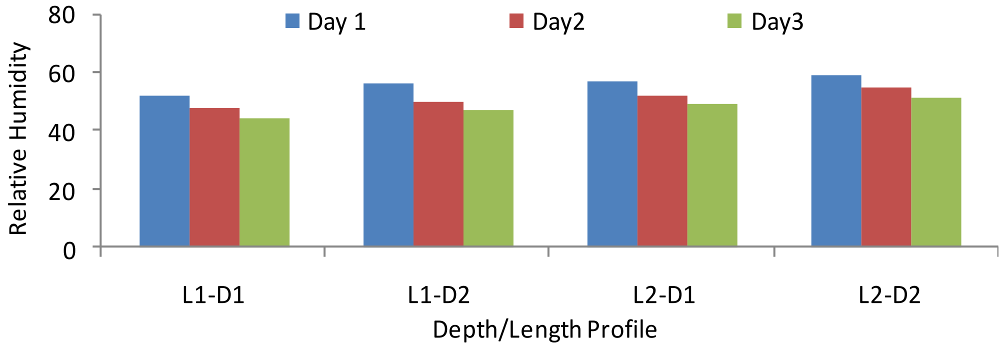


Fig. 5.29 Relative humidity profile versus time (GWT 3)

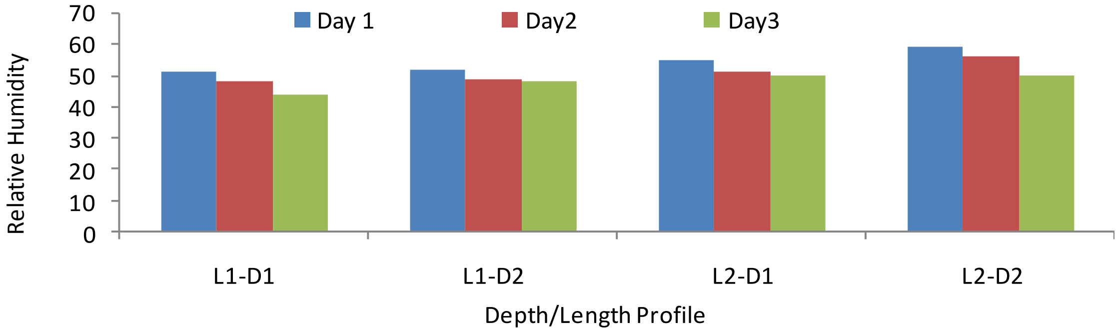


Fig. 5.30 Relative humidity profile versus time (GWT 4)

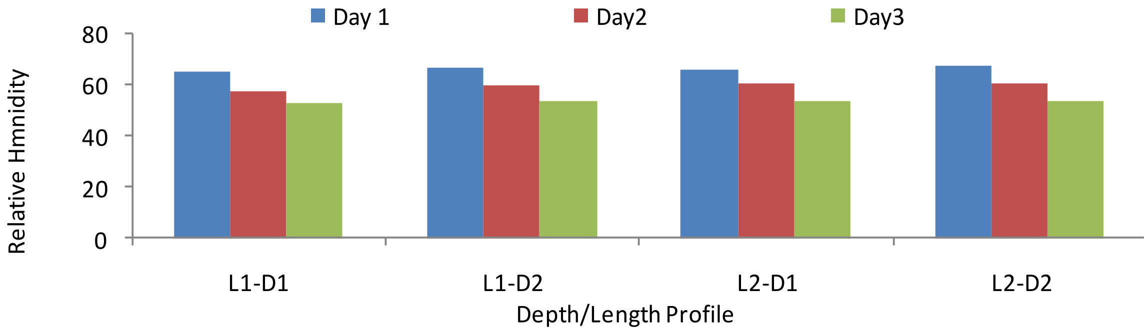


Fig. 5.31 Relative humidity profile versus time (GWT 5)

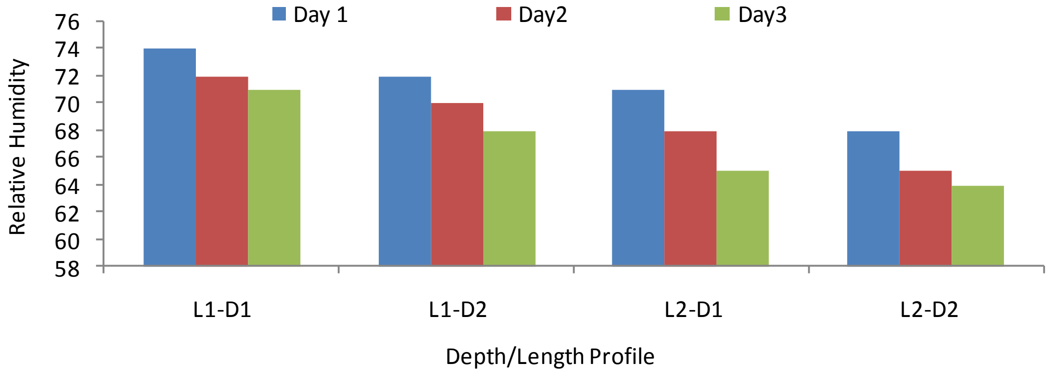


Fig. 5.32 Relative humidity profile versus time (GWT 6)

Figure 5.33 and 5.34 show the comparison of water content and comparison of removal of water for different types of woven conductive geotextiles. For GWT 1, the initial moisture content was observed 33.27% and final moisture content noted was 28.29% showing a reduction of 14.97%. For GWT 2, the moisture content was decreased from the initial value of 33.27% to 21.28% as indicated by percentage water reduction in moisture content by 36.04%. Figure 5.33 denotes the moisture content was decrease from initial value of 33.3% to 21.42% which observed percentage reduction was 35.69% for GWT 3. For GWT 4, the moisture content decreased from 33.27% to 21.38% and percentage reduction in moisture content was 35.74%. For GWT 5, the water content was decreased from 33.27% to 21.28 % showing a reduction of 36.038%. In case of GWT 5, the moisture content was decreased from the initial value of 33.27% to 24.42% indicated by percentage water reduction by 35.69%.

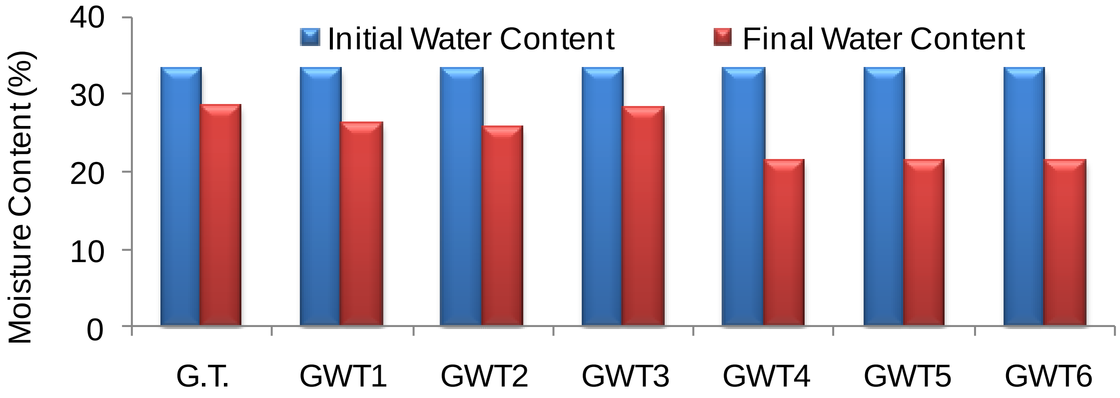


Fig. 5.33 Comparison of water content – Effect of type of woven conductive geotextile

Figure 5.35 shows the comparison of vane shear strength with passage of time along the length as well as depth of the reactor for different types of woven conductive geotextiles. For GWT 1, on passing current, the strength was increased gradual but significantly throughout the experiment. The final strength noted was 0.049 kg/cm^2 at the end of 72 hours showing an overall 23.10% increase in strength. For GWT 2, the strength gradually increased showing a rapid rise between 6 and 30 hours followed by gradual but significant increase throughout the experiment. The final strength observed was 0.053 kg/cm^2 at the end of the experiment (34.77%). For GWT 3, the strength gradually increased throughout the experiment. The final strength noted was 0.044 kg/cm^2 at the end of 72 hours showing an overall 10.66% increase in strength. For GWT 4, after applying current, the strength gradually increased showing rapid rise between 0 to 30 hours followed by steep rise between 30 and 54 hours followed by gradually increased. At the end of the experiment the strength noted was 0.0974 kg/cm^2 showing an overall 147.21% increase in strength. For GWT 5, on supplying current, the strength increased showing rapid rise throughout the experiments. The final strength observed was 0.105 kg/cm^2 at the end of the experiment (169.23%). For GWT 6, the strength gradually increased showing a rapid rise between 30 to 72 hours. The final strength observed was 0.1 kg/cm^2 at the end of the experiment (138.10%).

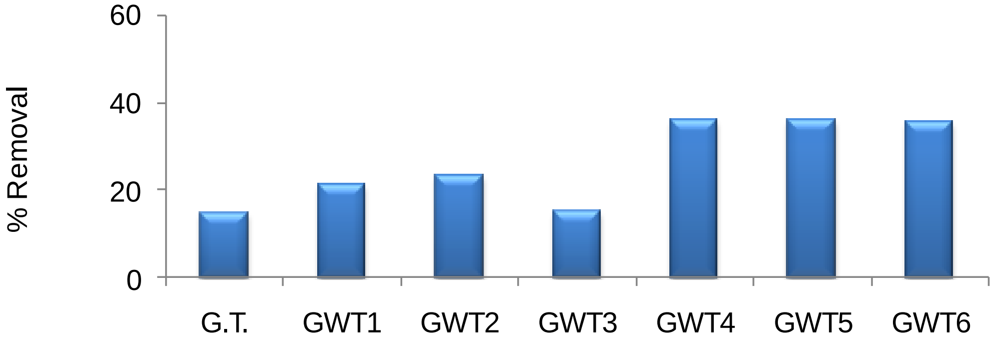


Fig. 5.34 Comparison of removal of water – Effect of type of woven conductive geotextile

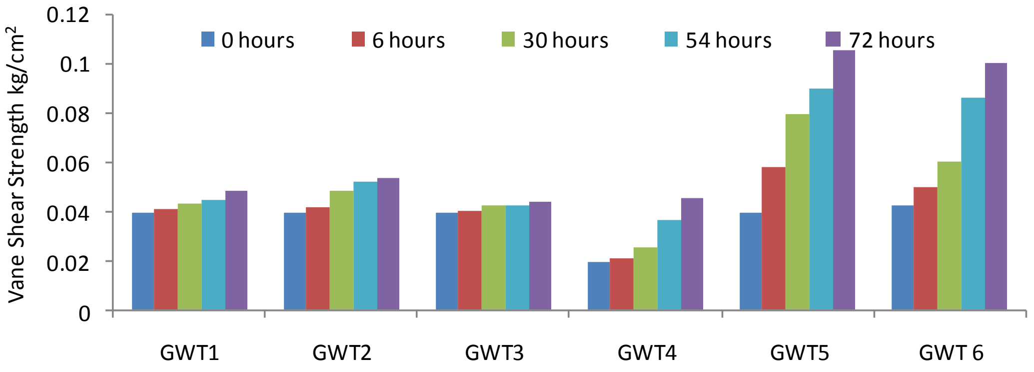


Fig. 5.35 Comparison of vane shear strength – Effect of type of woven conductive geotextile

Discussion:

Copper and steel filament was used to prepare conductive geotextiles. The time to maintain constant current using copper geotextile was higher compared to geotextile made up of steel filament. This may be attributed to the electrochemical reaction taking place at a rapid rate thereby increasing the electrical resistance. However, the effect can be controlled by the careful design of the electrode configuration with respect to the foundation shape and depth. If a metal electrode or a conductive woven geotextiles is used in place of carbon electrodes, the metal is bound to come in direct contact with soil. For example if steel electrodes are used in the experiments, it is expected that iron oxidation, dissociation and precipitation reactions shall occur at the anode thereby causing its corrosion. The severity of corrosion of the electrode during dewatering can be expressed as a function of current intermittence the mass of the anode can be measured before and after treatment for all electrokinetic tests. The degree of anode corrosion, S (%), is estimated by

$$S = \frac{M_o - M_f}{M_o} \times 100 = \frac{\Delta M}{M_o} \times 100$$

where M_o is the mass of the electrode before treatment (g); M_f is the mass of the electrode after treatment (g); and $\Delta M = M_o - M_f$ is the loss of electrode mass due to corrosion. The loss in the mass of the anode apparently shall affect the current density since the cross-sectional area of the treated soil shall be automatically reduced. The cathode shall remain intact in such cases, as understood from the theory of electrochemistry.

5.7.3 eKG as Conductive Vertical Geodrain for Dewatering

Analysis: Soil 2 was used for this phase. The maximum humidity was observed at section L1-D1 (54%) and minimum was observed at section L2-D1 and L2-D2 (51%). The moisture content was decreased by 56.67% to 40.81%. Fig. 5.36 shows the comparison of vane shear strength with passage of time along the length as well as depth of the reactor. On applying current, the strength gradual but significant increase was observed upto 30 hours followed by a steep rise between 30 and 54 hours followed by a gradual increase. At the end of the experiment the strength was noted 0.21 kg/cm^2 showing an overall 686.52% increase in strength.

Discussion: Comparison of the results of self weight consolidation tests and electroosmotic consolidation tests using electro vertical drains showed that electroosmosis was effective in strengthening of clayey sample. The study focused on the use of electrokinetics to enhance the effect of consolidation via vertical drains to improve the mechanical and physical properties of the deep layered soft clays or water logged areas after floods.

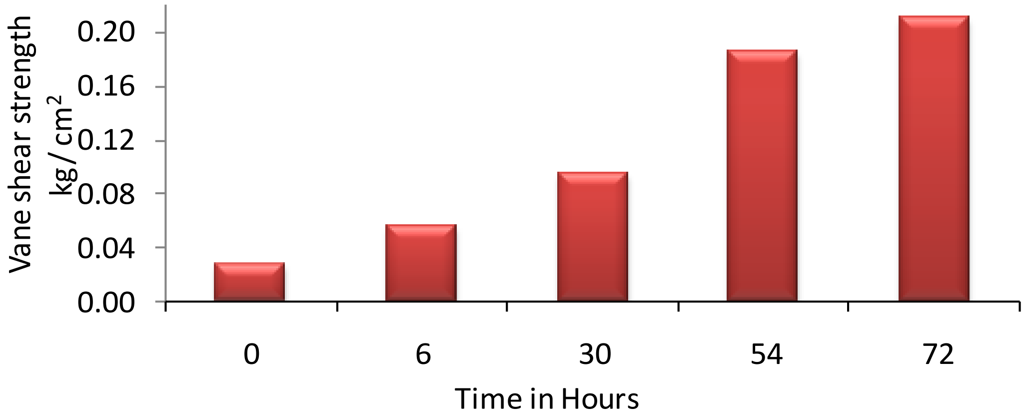


Fig. 5.36 Comparison of vane shear strength versus time – Use as a vertical geodrain

5.7.4 Effect of Type of Conductive Coating on Nonwoven Geotextile

Soil 4 was used for this phase. For CNW 1, figure 5.37 shows the relative humidity profile with time plot. The maximum humidity was observed at section L1-D1 (54%) and minimum was observed at L2-D1 and L2-D2 (51%). Figure 5.38 shows the relative humidity profile with time or CNWG 2. The maximum humidity was observed at section L2-D2 (38%) and minimum was observed at L1-D1 (32%).

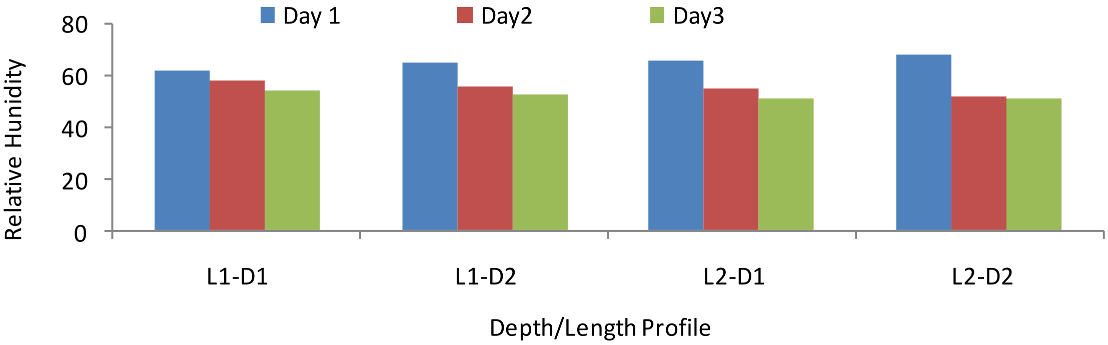


Fig. 5.37 Relative humidity profile versus time (CNW 1)

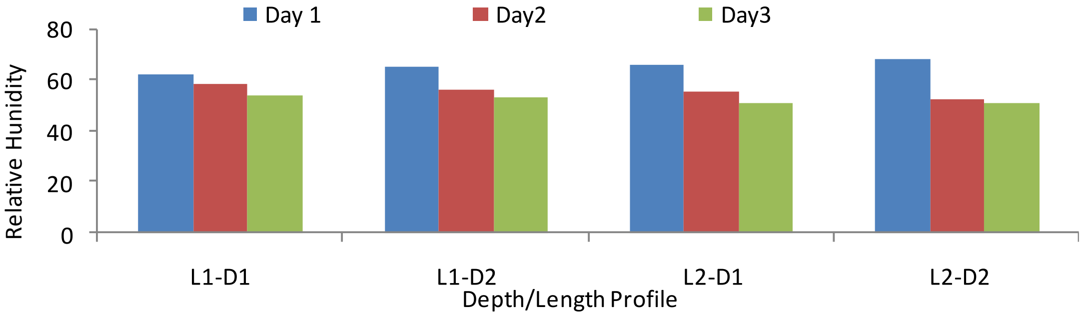


Fig. 5.38 Relative humidity profile versus time (CNW 2)

For CNWG 3, figure 5.39 shows the plot of relative humidity profile with time. The maximum humidity was observed at section L2-D2 (45%) and minimum was observed at L1-D1 (41%). Figure 5.40 and 5.41 shows the comparison of water content and comparison of removal of water for different type of conductive coating on nonwoven geotextiles. For CNWG 1, the initial moisture content observed was 28% and final moisture content was observed 25.9% showing a reduction 7.5%. In case of CNWG 2, the initial moisture content was decreased from initial value of 28% to 22% as indicated by percentage water reduction in moisture content by 24.42%. For CNWG 3, the moisture content decreased from 28% to 25.1%. And removal of water observed was 10.357%.

Figure 5.42 show the comparison of vane shear strength with passage of time along the length as well as depth of the reactor. For CNWG 1, on passing current through the setup, the strength gradually increased showing a rapid rise between 6 to 30 hours followed by a gradual but significant increase throughout the experiment. The final strength noted was 0.08 kg/cm^2 at the end of 72 hours showing an overall 322.11% increase in strength. For

CNWG 2, applying supply the strength was gradually but significantly increase showing a steep rise between 54 and 72 hours. At the end of the experiment the strength was noted 0.096 kg/cm^2 showing an overall 405.26% increase in strength. In case of CNWG 3, on passing current through the setup, the strength gradually increased showing a rapid rise between 6 and 30 hours followed by a gradual but significant increase throughout the experiment. The final strength noted was 0.084 kg/cm^2 at the end of 72 hours showing an overall 342.11% increase in strength.

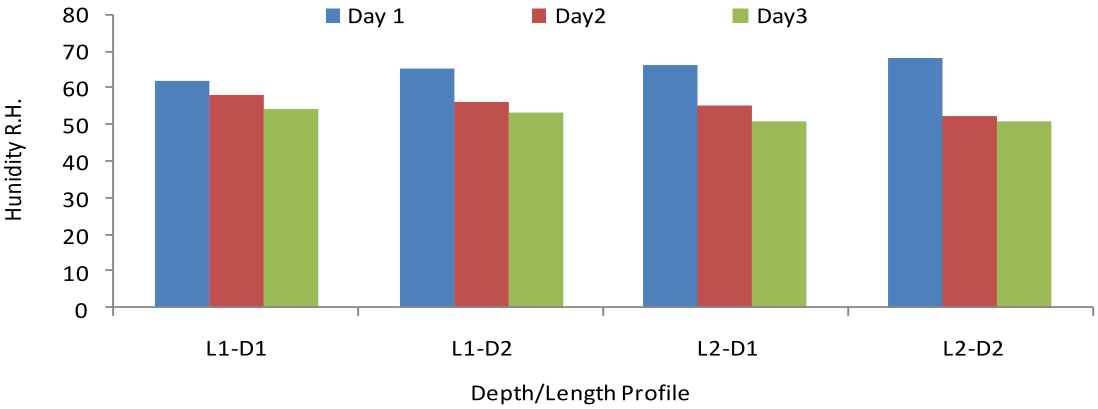


Fig. 5.39 Relative humidity profile versus time (CNW 3)

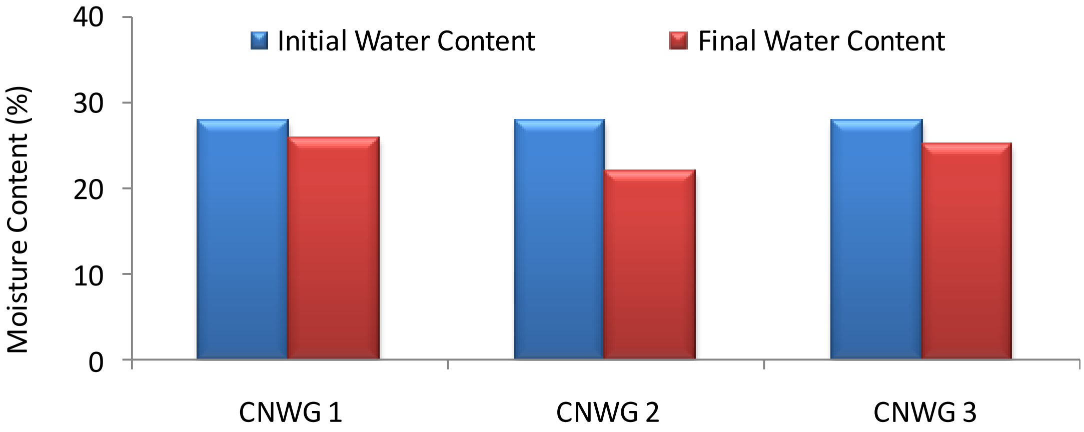


Fig. 5.40 Comparison of water content – Type of conductive coating on nonwoven geotextile

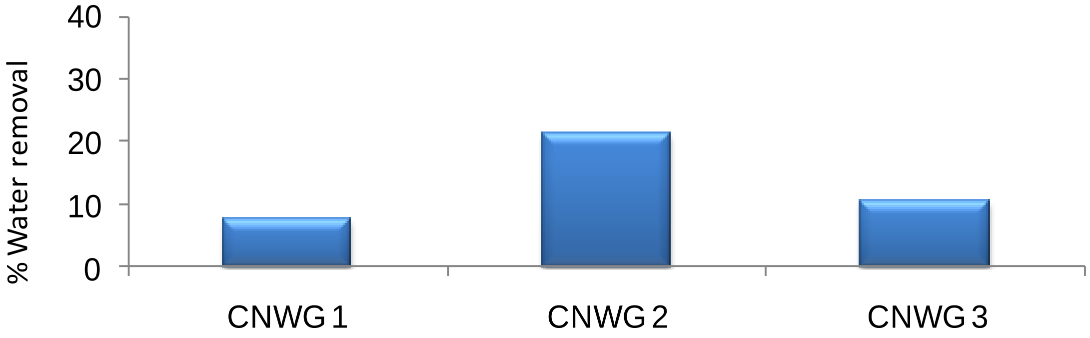


Fig. 5.41 Comparison of removal of water – Type of conductive coating on nonwoven geotextile

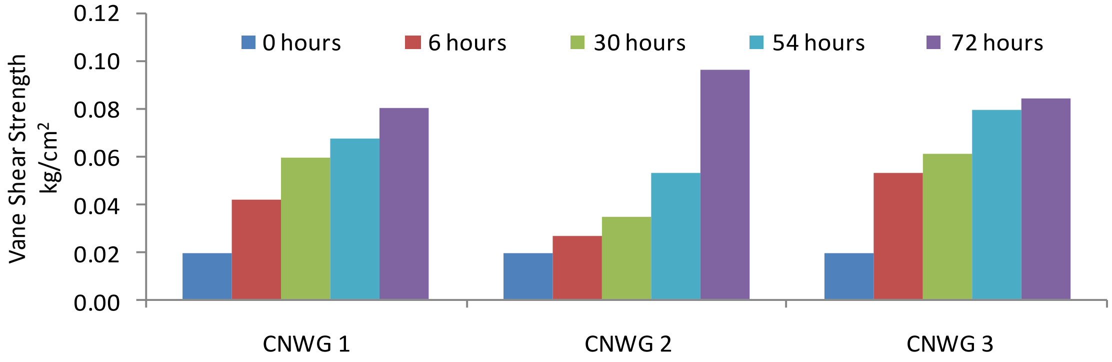


Fig. 5.42 Comparison of vane shear strength – Type of conductive coating on nonwoven geotextile

Discussion: The polycarbonate with emeraldine base shows lower percentage removal as opposed to nylon 6 since it does not form a composite there by reducing of efficiency for dewatering. This is attributed to lesser conductivity of the coated textile there by reducing electrolysis of water necessary for removal of water. As expected poly o-toluidine with nylon 6 gives reduced dewatering since it has lower conductivity as opposed to the EB with nylon 6.overall from this work it can be seen that nylon 6 with EB gives the best result through it further requirement refinement for commercial use.

5.7.5 Effect of Type of Conductive Coating on Nonwoven Geotextile for Re-Run

Soil 4 was used for this phase. For GR 1 the result data were similar to CNWG 3 and also for GR 2 the results were similar to CNWG 2. Figure 5.43 shows the plot of relative humidity profile with time for GR 1-1. The maximum humidity was observed at section L2-D1 (62%) and minimum was observed at L1-D1 (53%). For GR 2-1, figure 5.44 shows relative humidity profile with time plot. The maximum humidity was observed at section L2-D1 (48%) and minimum was observed at L1-D1 (38%). Figure 5.45 and 5.46 shows the comparison of water content and comparison of removal of water for different type of conductive coating on nonwoven geotextiles. For GR 1-1, the initial moisture observed was 28% followed by a reduction to 25.1%. So the water removal observed was 10.357%. For GR 2-1, the moisture content decrease from 28 % to 25.9% as indicated by percentage water reduction in moisture content by 7.5%.

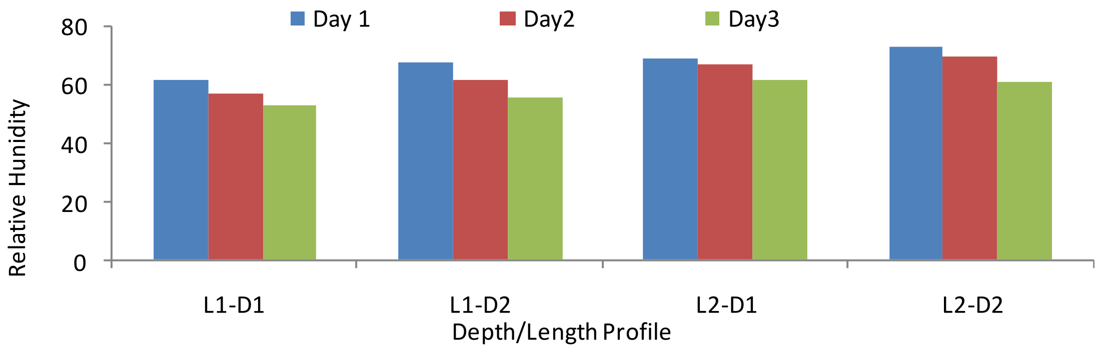


Fig. 5.43 Relative humidity profile versus time (GR 1-1)

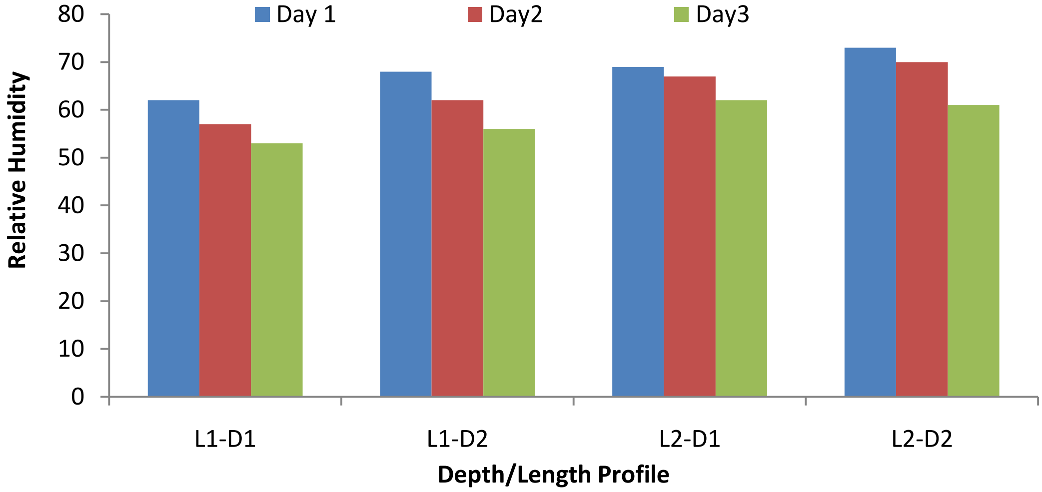


Fig. 5.44 Relative humidity profile versus time (GR 2-1)

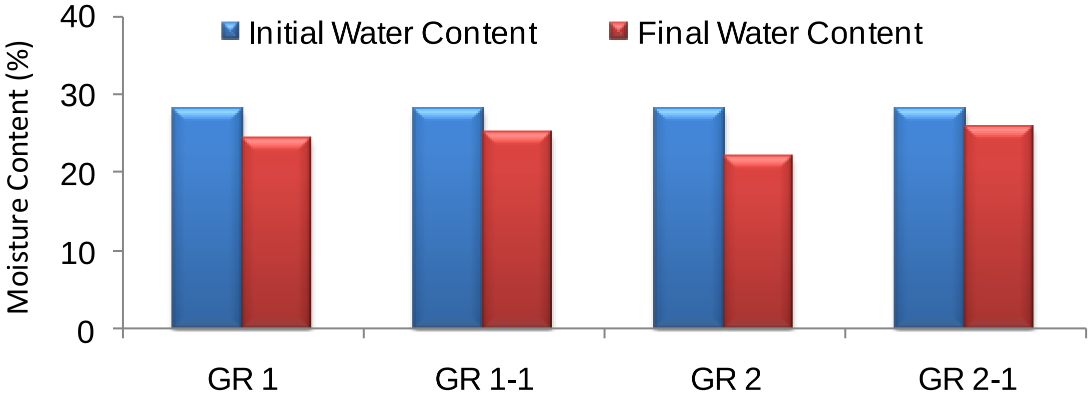


Fig. 5.45 Comparison of water content – Effect of type of conductive coating on nonwoven geotextile for re-run

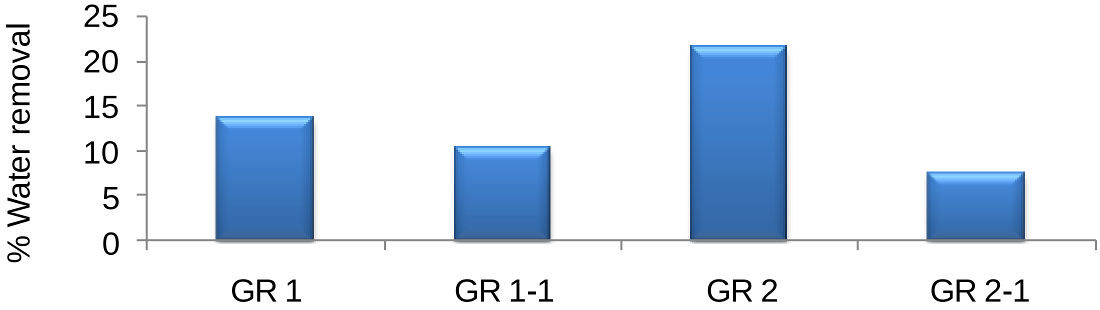


Fig. 5.46 Comparison of removal of water – Effect of type of conductive coating on nonwoven geotextile for re-run

Figure 5.47 show the comparison of vane shear strength with passage of time along the length as well as depth of the reactor. For GR 1-1, on applying current, the strength gradually increased showing a rapid rise between 6 and 30 hours followed by a gradual but significant increase throughout the experiment. At the end of the experiment the final strength was noted 0.589 kg/cm^2 showing an overall 210.00% increase in strength. For GR 2-1, the strength gradually increased showing a rapid rise between 6 and 30 hours followed by a gradual but significant increase again showing rapid rise between 54 and 72 hours. The final strength observed was 0.561 kg/cm^2 at the end of 72 hours showing an overall 195.26% increase in strength. It was clear from the comparative graph that the vane shear strength obtain in second run was less compare to first run.

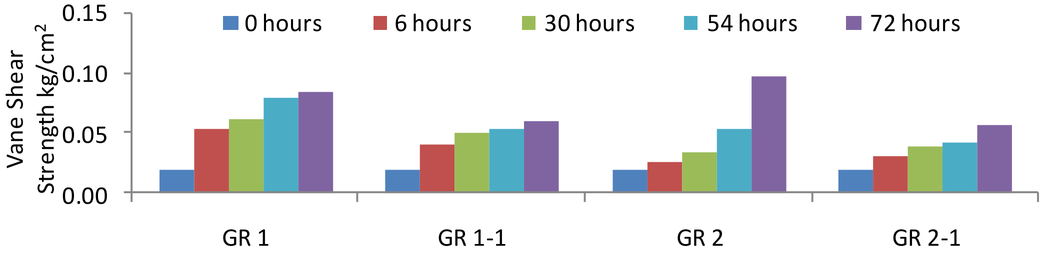


Fig. 5.47 Comparison of vane shear strength – Effect of type of conductive coating on nonwoven geotextile for re-run

Discussion: The re-run experiment with emeraldine base with nylon6 did not show any appreciable change in the percentage removal but for the coated textile using poly o-toludine with nylon 6 showing an appreciable decrease in the percentage of water removal.

5.7.6 Effect of Material Composition on Conductive Coating for Dewatering

Soil 4 and Soil 6 was used for this phase. The results of SCC 1 were similar to CNWG 1. For SCC 2, figure 5.48 shows the relative humidity profile with time. The maximum humidity was observed at section L2-D2 (38%) and minimum was observed at section L1-D1 (32%). Figure 5.49 and 5.50 show the comparison of water content and comparison of water reduction versus time. The initial water content noted was 33.27% which reduced to 27.32% i.e. the reduction in water observed was 17.88%. Figure 5.51 shows the comparison of vane shear strength with passage of time along the length as well as depth of the reactor. For SCC 2, on applying current, the strength gradually increased showing a rapid rise between 6 to 30 hours followed by a gradual but significant increase throughout the experiment.

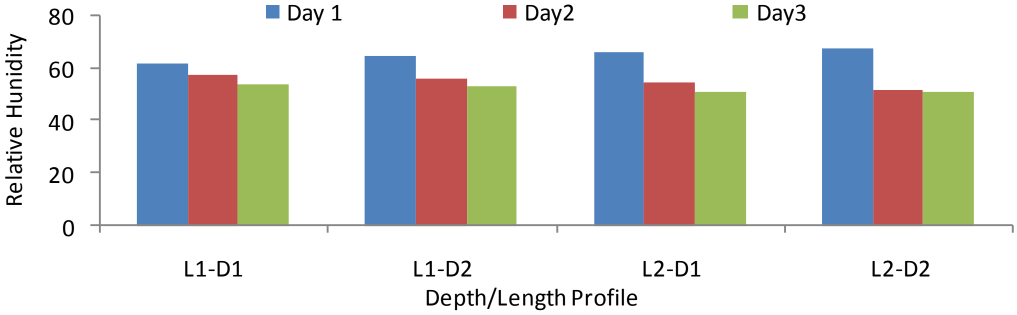


Fig. 5.48 Relative humidity profile versus time (SCC 1)

The removal of water silty soil is much better since the water holding capacity of soil compared to black cotton clayey soil is much less thereby offering reduced resistance to water movement under the same applicable voltage gradient. The removal percentage can be increased by increasing the voltage gradient rather than duration of test.

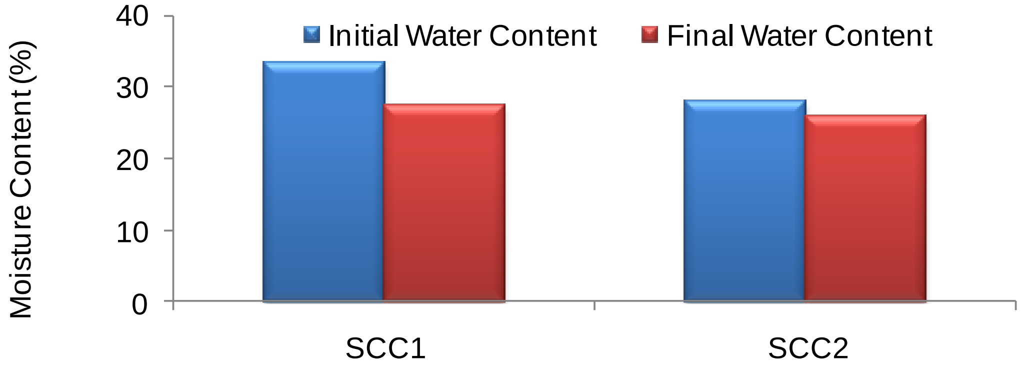


Fig. 5.49 Comparison of water content – Effect of soil type on conductive coating

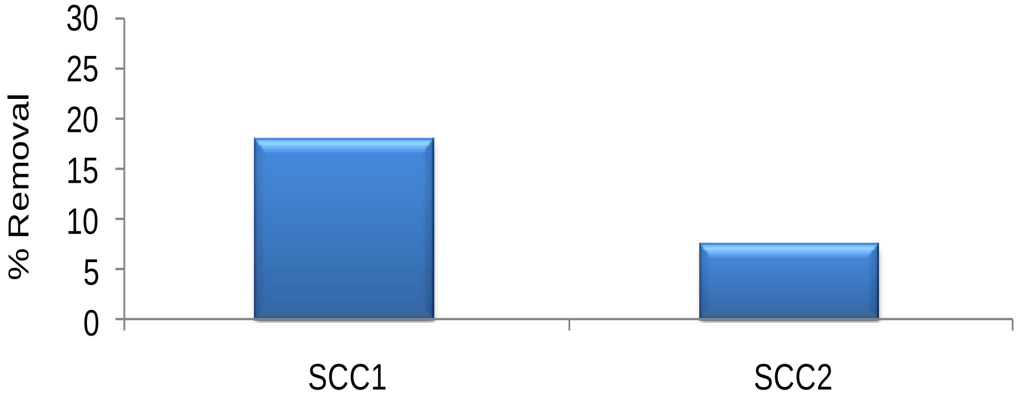


Fig. 5.50 Comparison of removal of water – Effect of soil type on conductive coating

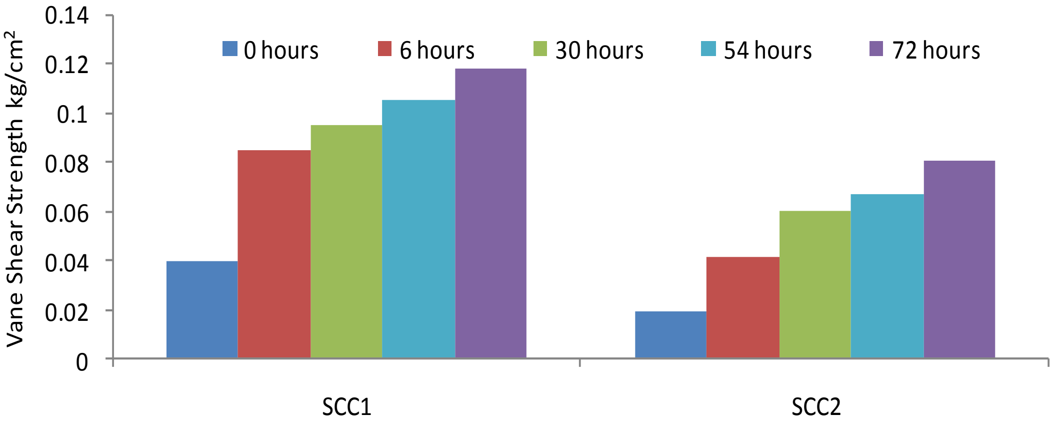


Fig. 5.51 Comparison of vane shear strength – Effect of soil type on conductive coating

5.8 CONCLUSIONS

Based on the discussions the following conclusions can be drawn:

- The increase in shear strength at the anode and central regions was predominantly a result of electroosmosis, whereas the increase in shear strength in the cathode region resulted from cementation due to intensive precipitation of amorphous cementing agents.

- The strengthening effect is directly associated with the applied electric field intensity. The technique of current intermittence can significantly reduce the power consumption and electrode corrosion.
- The application of an electric field to the marine sediment generated a pH gradient across the electrodes and increased the electrical conductivity of the soil pore fluid in the electrode regions. Due to the significant local strengthening effect at the anode and cathode regions, this method has potential applications in strengthening soft marine soils at and around the location of anchors, driven piles, suction caissons, and other foundation elements of new onshore and offshore structures and for rehabilitation of existing offshore platforms.

CHAPTER 6

MODELLING AND MULTIPLE LINEAR REGRESSIONS

Modelling and Multiple Linear Regressions

Chapter Six

6.1 INTRODUCTION

Mathematical modeling is an attempt to describe some part of the real world in mathematical terms. It is an endeavor as old as antiquity but as modern as tomorrow's newspaper. It has led to some good mathematical models and some bad ones, which are best forgotten. Sometime mathematical models have been welcomed with great enthusiasm – even when their value was uncertain or negligible; other time good mathematical models have been greeted with indifference, hostility, or ridicule. Mathematical models shave been built in the physical, biological, and social sciences. The building blocks for these models have been taken from calculus, algebra, geometry, and nearly every other field within mathematics. In short, mathematical modeling is a rich and diverse activity with many interesting aspects. In ordinary language the word "model" has many meanings.

- **Definition**

A model is an object or concept that is used to represent something else. It is reality scaled down and converted to a form we can comprehend. It means a model whose parts are mathematical concepts such as constants, variable, functions, equations and inequalities.

6.2 NEED OF MATHEMATICAL MODELLING

Data obtained from experiments needs to be treated in a number of different ways to get meaningful insight into the system being studied. Numerous modeling techniques and multiple models may be developed for engines system. It is important to select a suitable modeling technique to capture the relationship between input and output of the system accurately and efficiently. For systems involving mutually conflicting out comes effected by a number of input variables it is essential to determine the optimum state of the system to achieve desired output by setting appropriate levels of inputs. For this purpose, use of suitable optimization technique is an essential.

With increase in knowledge about a system or process, its complexity decreases and understanding increases. Decrease in complexity leads to increase in precision afforded by computational methods useful in modeling of the system or process. As seen in Figure 6.1, for systems that are little complex and hence little uncertain, closed form mathematical models provide precise description of system. For systems little more complex but for which significant data is available, model free methods like artificial neural networks provide powerful and robust means to reduce uncertainty using pattern based learning. For most complex systems where little numerical data exists and where only ambiguous or imprecise information may be available, fuzzy models provide a method to understand and represent system behaviour by interpolation between observed inputs and outputs.

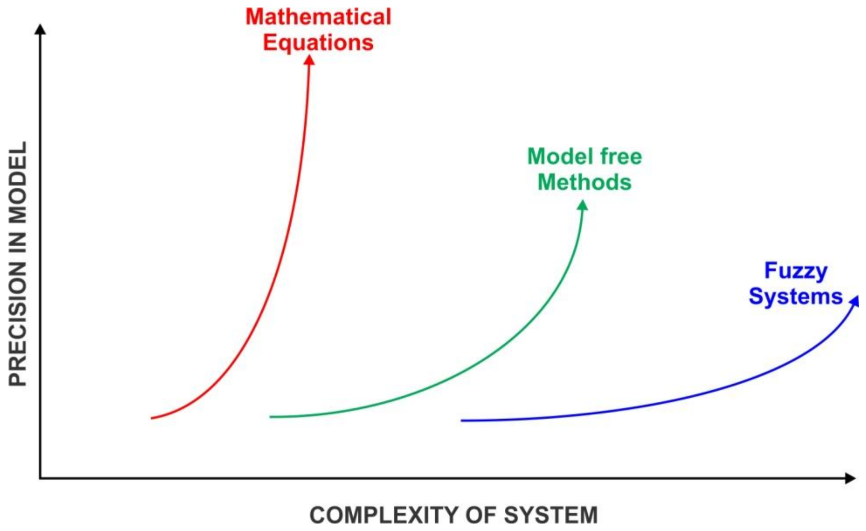


Fig. 6.1 Complexity of System & Precision Level of Different Models

6.3 METHODS OF MODELLING

There are several methods of modeling depending on the type of data, complexity of the data, its variation along the data set, types of variables, their distribution and dependency on other variable, etc. Depending on several such factors the type of modeling methodology is to be selected. Below mentioned are some of the common forms used for modeling.

- Modeling with difference equations
- Modeling with Ordinary Differential Equations
- Modeling with Partial Differential Equation
- Optimization
- Modeling with Simulations
- Function Fitting: Data Modeling

6.4 AN ALGORITHM FOR MODELING

The modeling process has a sequence of common steps that serve as an abstraction for the modeler:

- Identify the problem and questions.
- Identify the relevant variables in a problem.
- Simplify until tractable.
- Relate these variables mathematically.
- Solve.
- Does the solution provide added value?
- Tweak model and compare solutions.

6.5 THE DELICATE SCIENCE OF ERRORS

If one had either infinite time or infinite computing power error analysis would presumably be a derelict activity: all models would be absolutely accurate. Obviously, in reality, this is not the case and a well-accepted modus operandi in modeling is committing admissible errors. Of course, in practice, the science is more ad hoc. If terms in an equation introduce computational difficulties the immediate question arises as to what would happen if those terms are ignored? In theory we would rather keep them but in practice we can't afford to. Thus the delicate science of modeling concerns retaining just enough features to make the model useful but not so many as too make it more expensive to compute than necessary to get out the desirable information. We illustrate this concept by examining the seemingly innocuous school problem

$$\epsilon x^2 + x + 1 = 1$$

Of course we can solve this problem exactly using the quadratic formula

$$x = -\frac{1}{2\epsilon} \pm \frac{\sqrt{1-4\varepsilon}}{2\epsilon}$$

For a moment, let us assume that the quadratic term were actually an unknown term, e.g.,

$$\epsilon \mathrm{f(x)} + \mathrm{x} + 1 = 0$$

and that actually computing f might be rather expensive. We might argue that if Є were very small that this term could safely be ignored. Now let us return to the simple case of f(x) = x^2. If Є is taken as zero then clearly it follows that x = −1, is the unique solution. However, we know from our quadratic equation however that if Є = 0.0000001 (any non-zero number would do), then there are two solutions rather than one. So we have actually lost a potentially important solution by ignoring what appeared to be a small quantity. In addition, we may also have introduced inaccuracies into the obtained solution and this issue must be explored. In essence we are concerned with how quickly the solution changes about the point Є = 0. To see how this solution changes as a function of Є consider the series expansion

$$x = a_0 + a_1\epsilon + a_2\epsilon^2 + a_3\epsilon^3 + \ldots\ldots\ldots\ldots$$

Substituting this expansion into the original quadratic results in the new equation

$$a_0 + 1 + (a_0^2 + a_1)\epsilon + (2a_0a_1 + a_2)\epsilon^2 + \ldots\ldots\ldots\ldots = 0$$

Setting the coefficients of the different powers of ² to zero gives the series solution for x as

$$x = -1 - \epsilon - 2\epsilon^2 + \ldots\ldots\ldots\ldots$$

So if Є ≈ 0.01 we can conclude the error is on the order of 1% and the error will grow quickly with Є .

6.6 REGRESSION ANALYSIS

Regression analysis is one of the most widely used statistical tools because it provides simple methods for establishing a functional relationship among variables. It is a conceptually simple method for investigating functional relationships among variables. A real estate appraiser may wish to relate the sale price of a home from selected physical characteristics of the building and taxes (local, school, county) paid on the building. We may wish to examine whether cigarette consumption is related to various socioeconomic and demographic variables such as age, education, income, and price of cigarettes. The relationship is expressed in the form of an equation or a model connecting the response or dependent variable and one or more explanatory or predictor variables. In the cigarette consumption example, the response variable is cigarette consumption (measured by the number of packs of cigarette sold in a given state on a per capita basis during a given year) and the explanatory or predictor variables are the various socioeconomic and demographic variables. In the real estate appraisal example, the response variable is the price of a home and the explanatory or predictor variables are the characteristics of the building and taxes paid on the building. We denote the response variable by Y and the set of predictor variables by X_1, X_2 ,…. X_p, where p denotes the number of predictor variables. The true relationship between Y and X_1, X_2 ,…. X_p can be approximated by the regression model

$$Y = F\left(\mathrm{X}_1, \mathrm{X}_2 \ldots\ldots \mathrm{X}_\mathrm{p}\right) + \epsilon \text{ --------(6.1)}$$

where ε is assumed to be a random error representing the discrepancy in the approximation. It accounts for the failure of the model to fit the data exactly. The function $f(X_1, X_2, \ldots, X_p)$ describes the relationship between Y and X_1, X_2 ,…. X_p . An example is the linear regression model

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots\ldots\ldots\ldots\ldots + \beta_p X_p + \epsilon \text{ --------(6.2)}$$

where β_0, β_1……. β_p are called the regression parameters or coefficients, are unknown constants to be determined (estimated) from the data. We follow the commonly used notational convention of denoting unknown parameters by Greek letters. The predictor or explanatory variables are also called by other names such as independent variables, covariates, regressors, factors, and carriers. The name independent variable, though commonly used, is the least preferred, because in practice the predictor variables are rarely independent of each other.

6.7 STEPS IN REGRESSION ANALYSIS

Regression analysis includes the following steps:

- Statement of the problem
- Selection of potentially relevant variables
- Data collection
- Model specification
- Choice of fitting method
- Model fitting
- Model validation and criticism
- Using the chosen model(s) for the solution of the posed problem.

6.7.1 Statement of the Problem

Regression analysis usually starts with a formulation of the problem. This includes the determination of the question(s) to be addressed by the analysis. The problem statement is the first and perhaps the most important step in regression analysis. It is important because an ill-defined problem or a misformulated question can lead to wasted effort. It can lead to the selection of irrelevant set of variables or to a wrong choice of the statistical method of analysis. A question that is not carefully formulated can also lead to the wrong choice of a model.

6.7.2 Selection of Potentially Relevant Variables

The next step after the statement of the problem is to select a set of variables that are thought by the experts in the area of study to explain or predict the response variable. The response variable is denoted by Y and the explanatory or predictor variables are denoted by X_1, X_2, . . . , X_p, where p denotes the number of predictor variables..

6.7.3 Data Collection

The next step after the selection of potentially relevant variables is to collect the data from the environment under study to be used in the analysis. Sometimes the data are collected in a controlled setting so that factors that are not of primary interest can be held constant. More often the data are collected under non-experimental conditions were very little can be controlled by the investigator. In either case, the collected data consist of observations on n subjects. Each of these n observations consists of measurements for each of the potentially relevant variables. In regression analysis, the predictor variables can be either quantitative and/or qualitative. For the purpose of computations, however, the qualitative variables, if any, have to be coded into a set of indicator or dummy variables. If all predictor variables are qualitative, the techniques used in the analysis of the data are called the analysis of variance techniques. If some of the predictor variables are quantitative while others are qualitative, regression analysis in these cases is called the analysis of covariance.

6.7.4 Model Specification

The form of the model that is thought to relate the response variable to the set of predictor variables can be specified initially by the experts in the area of study based on their knowledge or their objective and/or subjective judgments. The hypothesized model can then be either confirmed or refuted by the analysis of the collected data. Note that the model needs to be specified only in form, but it can still depend on unknown parameters. We need to select the form of the function f (X_l, X_2, . . . , X_p). This function can be classified into two types: linear and nonlinear. An example of a linear function is

$$Y = \beta_0 + \beta_1 x_1 + \epsilon \text{ -------- (6.3)}$$

while a nonlinear function is

$$Y = \beta_0 + e^{\beta_1 x_1} + \epsilon \text{ -------- (6.4)}$$

Note that the term linear (nonlinear) here does not describe the relationship between Y and X_1, X_2, ……X_p. It is related to the fact that the regression parameters enter the equation linearly (nonlinearly). Each of the following models are linear

$$Y = \beta_0 + \beta_1 x + \beta_2 x^2 + \epsilon$$
$$Y = \beta_0 + \beta_1 \ln x + \epsilon$$

because in each case the parameters enter linearly although the relationship between Y and X is nonlinear. This can be seen if the two models are re-expressed, respectively, as follows:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \epsilon$$
$$Y = \beta_0 + \beta_1 x_1 + \epsilon$$

where in the first equation we have $X_1 = X$ and $X_2 = X^2$ and in the second equation we have $X_1 = \ln X$. The variables here are re-expressed or transformed. All nonlinear functions that can be transformed into linear functions are called linearizable functions. Accordingly, the class of linear models is actually wider than it might appear at first sight because it includes all linearizable functions. Note, however, that not all nonlinear functions are linearizable.

A regression equation containing only one predictor variable is called a simple regression equation. An equation containing more than one predictor variable is called a multiple regression equation. In certain applications the response variable can actually be a set of variables, Y_1, Y_2,. . ., Y_p, say, which are thought to be related to the same set of predictor variables, X_1 , X_2, . ., X_p. When we deal only with one response variable, regression analysis is called univariate regression and in cases where we have two or more response variables, the regression is called multivariate regression. Simple and multiple regressions should not be confused with univariate versus multivariate regressions. The distinction between simple and multiple regressions is determined by the number of predictor variables (simple means one predictor variable and multiple means two or more predictor variables), whereas the distinction between univariate and multivariate regressions is determined by the number of response variables (univariate means one response variable and multivariate means two or more response variables). The various classifications of regression analysis we discussed above are shown in Table 1.1.

6.7.5 Method of Fitting

After the model has been defined and the data have been collected, the next task is to estimate the parameters of the model based on the collected data. This is also referred to as parameter estimation or model fitting. The most commonly used method of estimation is called the least squares method. Under certain assumptions, least squares method produce estimators with desirable properties. In some instances (e.g., when one or more of the assumptions does not hold) other estimation methods may be superior to least squares. The other estimation methods that can be considered are the maximum likelihood method, the ridge method, and the principal components method.

Table 6.1 Various Classifications of Regression Analysis

Type of Regression	Conditions
Univariate	Only one quantitative response variable.
Multivariate	Two or more quantitative response variables.
Simple	Only one predictor variable.
Multiple	Two or more predictor variables.
Linear	All parameter enter the equation linearly, possible after transformation of the data.
Non Linear	Relationship between the response and some of the predictors is nonlinear or some of the parameters appear nonlinearly, but no transformation is possible to make the parameters appear linearly.
Analysis of Variance	All predictors are qualitative variables.
Analysis of Covariance	Some predictors are quantitative variables and other are qualitative variables.
Logistic	The response variable is qualitative.

6.7.6 Model Fitting

The next step in the analysis is to estimate the regression parameters or to fit the model to the collected data using the chosen estimation method (e.g., least squares). The estimates of the regression parameters $\beta_0,\beta_1,\ldots\beta_p$ in (1.l) are denoted by $\widehat{\beta_0}$, $\widehat{\beta_1}$,& , . . . , $\widehat{\beta_p}$. The estimated regression equation then becomes

$$\hat{Y} = \widehat{\beta_0} + \widehat{\beta_1}\, X_1 + \widehat{\beta_2}\, X_2 + \ldots\ldots\ldots\ldots + \widehat{\beta_p}\, X_p \quad \text{--------(6.5)}$$

A hut on top of a parameter denotes an estimate of the parameter. The value $\hat{Y}$ (pronounced as Y-hat) is called the fitted value. Using (1.5), we can compute n fitted values, one for each of the n observations in our data. It is interesting to notes that (1.5) can be used to predict the response variable for any values of the predictor variables not observed in our data. In this case, the obtained Y is called the predicted value. The difference between fitted and predicted values is that the fitted value refers to the case where the values used for the predictor variables correspond to one of the n observations in our data, but the predicted values are obtained for any set of values of the predictor variables. It is generally not recommended to predict the response variable for a set of values of the predictor variables far outside the range of our data. In cases where the values of the predictor variables represent future values of the predictors, the predicted value is referred to as the forecasted value.

6.7.7 Model Criticism and Selection

The validity of a statistical method, such as regression analysis, depends on certain assumptions. Assumptions are usually made about the data and the model. The accuracy of the analysis and the conclusions derived from an analysis depends crucially on the validity of these assumptions. Before using (1.5) for any purpose, we first need to determine whether the specified assumptions hold. We need to address the following questions:

- What are the required assumptions?
- For each of these assumptions, how do we determine whether or not the assumption is valid?
- What can be done in cases where one or more of the assumptions does not hold?

The standard regression assumptions will be specified and the above questions will be addressed in great detail in various parts of this book. We emphasize here that validation of the assumptions must be made before any conclusions are drawn from the analysis. Regression analysis is viewed here as a iterative process, a process in which the outputs are used to diagnose, validate, criticize, and possibly modify the inputs. The process has to be repeated until a satisfactory output has been obtained. A satisfactory output is an estimated model that satisfies the assumptions and fits the data reasonably well. This iterative process is illustrated schematically in Figure 6.2.

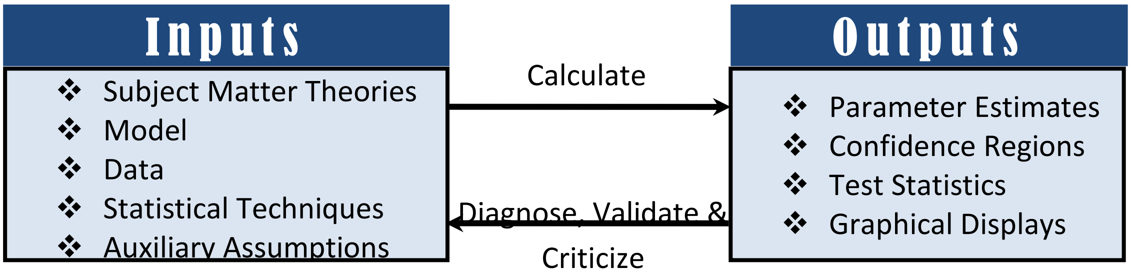


Fig. 6.2 A Schematic Illustration of the Iterative Nature of Regression Process

6.7.8 Objectives of Regression Analysis

The explicit determination of the regression equation is the most important product of the analysis. It is a summary of the relationship between Y (the response variable) and the set of predictor variables X_1 , X_2, . . . , X_p,. The equation may be used for several purposes. It may be used to evaluate the importance of individual predictors, to analyze the effects of policy that involves changing values of the predictor variables, or to forecast values of the response variable for a given set of predictors. Although the regression equation is the final product, there are many important by-products. We view regression analysis as a set of data analytic techniques that are used to help understand the interrelationships among variables in a certain environment. The task of regression analysis is to learn as much as possible about the environment reflected by the data. We emphasize that what is uncovered along the way to the formulation of the equation may often be as valuable and informative as the final equation.

6.8 REGRESSION MODEL FOR ELECTROKINETIC REMEDIATION OF NICKEL CONTAMINATED SOIL

The regression modeling is carried out for find out the relation between the percentage output removal and other input variables studied in the experimental work. Some of the input variables were of the qualitative form i.e. name of the anodic and cathodic solution used at the compartments; this necessitated the conversion of this input variable in form of a numeric input. The range of the variables involved varied over a large range from 0.00001 to 500 which increases the need for scaling the variables to bring the range in a common range facilitating the regression modeling. This was affected by use of scaling factors for the different variables. We will consider eighteen variables for which the various statistical parameters have been found and tabulated below in Table 6. 2. Table 6.3 gives details of the scaling factors used to convert the original values to the scaled values. Table 6.4 gives the details of numeric values used to convert qualitative inputs into quantitative inputs depending on their effectiveness in nickel removal. The dependent variable will be Output_1 and we will investigate whether we can explain variation in percentage of removal with Input1, Input_2,…Input17. We will consider:

- Whether this model makes sense substantively
- Whether the usual assumptions of multiple linear regression analysis are met with these data.
- How much variation in Percentage of removal the seventeen explanatory variables explain
- Which explanatory variables are most ‘important’ in this model
- What is the nature of the relationship between Percentage of removal and the explanatory variables

It is first required to do some exploratory data analysis (EDA). It is always a good idea to precede a regression analysis with EDA. Table 6.5 shows the descriptive statistics and its improvement due to scaling over the unscaled variables as shown in Table 6.2

6.8.1 Bivariate EDA Correlation Analysis:

In a bivariate distribution one is interested to find if there is any relationship between the two variables under study. The correlation is a statistical tool which studies the relationship between two variables and correlation analysis involves various methods and techniques used for studying and measuring the extent of the relationship between the two variables. The variables are said to be correlated if the change in one variable results in a corresponding change in the other variable. The formula for Correlation Coefficient between x and y is given by

$$r_{xy} = {}^{cov(x,y)}/_{\sigma_x \sigma_y}$$

Table 6.2 List of variable and Descriptive Statistics (Unscaled Values)

Variable	Parameter						
	N	Range	Minimum	Maximum	Mean	Standard Deviation	Variance
Percentage of removal (Output_1)	96	56.95	32.84	89.79	74.73	10.91	119.11
Initial Concentration (Input_1)	96	250.00	250.00	500.00	372.92	106.60	11364.04
Anode Solution (Input_2)	96	Qualitative Input					
Conc. Of Anode (Input_3)	96	0.90	0.10	1.00	0.93	0.24	0.06
Cathode Solution (Input_4)	96	Qualitative Input					
Conc. Of Cathode (Input_5)	96	0.90	0.10	1.00	0.3	0.37	0.14
Voltage Applied (Input_6)	96	29.17	8.33	37.50	23.59	7.61	57.92
Current (Input_7)	96	0.63	0.01	0.64	0.15	0.13	0.02
Current Density (Input_8)	96	0.06	0.00	0.06	0.01	0.01	0.00
Ambient Temperature (Input_9)	96	13.42	23.69	37.12	31.39	4.30	18.50
Temp. Anode (Input_10)	96	31.81	23.11	54.92	33.74	6.62	43.88
Temp. Center (Input_11)	96	25.56	23.57	49.13	33.82	5.71	32.59
Temp. Cathode (Input_12)	96	419.65	23.51	443.16	37.47	42.14	1775.95
Voltage Anode (Input_13)	96	20.10	1.09	21.19	5.20	3.91	15.31
Voltage Center (Input_14)	96	22.45	2.07	24.52	9.03	4.92	24.16
Voltage Cathode (Input_15)	96	25.94	4.48	30.42	14.42	7.21	51.95
Length of Sample (Input_16)	96	56.94	34.50	91.44	40.89	15.65	244.81
Cross Sectional Area (Input_17)	96	60.80	20.27	81.07	25.97	17.82	317.43

Table 6.3 Scaling Factors for Different Input and Output Variables for Electrokinetic Remediation of Nickel Contaminated Soil

Quantity	Scaling Factor
Initial Concentration (X)	= X/1000*1.5
Anode Solution (AS)	As per Table 6.4
Conc. Of Anode (Y)	= SQRT(Y)
Cathode Solution (CS)	As per Table 6.4
Conc. Of Cathode (Z)	= SQRT(Z)
Voltage Applied (V)	= V/100*2
Current (C)	= (SQRT((LOG(C))*-0.1))*1.25
Current Density (CD)	= (SQRT((LOG(CD))*-0.1))*1.25
Ambient Temperature (AT)	= AT*2/100
Temp. Anode (TA)	= TA/100*1.5
Temp. Center (TCe)	= TCe/100*1.5
Temp. Cathode (TC)	= TC/100*1.5
Voltage Anode (VA)	= (SQRT(VA/100))*1.5
Voltage Center (VCe)	= SQRT(VCe/100))*1.5
Voltage Cathode (VC)	= (SQRT(VC/100))*1.5
Length of Sample (L)	= L/150
Cross Sectional Area (CS)	= CS/100
Output - % Removal (OR)	= OR/100

Table 6.4 Scaling Factor for Qualitative Input Parameters

Anode Solution		**Cathode Solution**	
Chemical	Scaled Value	Chemical	Scaled Value
Sodium Chloride	0.15	Ethylene Diamine Tetra Acetic Acid	0.15
Perchloric Acid	0.25	Citric Acid	0.25
Butric Acid	0.35	Sodium Nitrite	0.35
Acetic Acid	0.45	Acetic Acid	0.45
Citric Acid	0.55	Tween 80*	0.55
Magnesium Chloride	0.65	Ortho Phosphoric Acid	0.65
Calcium Chloride	0.75	Igepal	0.75

* (Polyoxyethylene (20) Sorbittan Mono Oleate)

In addition to being able to predict the (mean) response at various levels of the independent variable, regression data can also be used to test for the independence between the two variables under investigation. Such a statistical test can be viewed or approached through the coefficient of correlation. The correlation coefficient r measures the strength of the relationship between two variables. It is an estimate of an unknown population correlation coefficient ρ (rho). If the value of the correlation coefficient is positive then the two variables are said to be positively correlated. If the value of the correlation coefficient is negative then the two variables are said to be negatively correlated. Correlation coefficient between Percentage of removal and set of independent variables and their significance test is tabulated in Table 6.6. For the correlation to be significant the following ratio of H_0: The correlation between percentage of removal and Anode Solution is not significant against H_1: The correlation between percentage of removal and Anode Solution is significant is to be calculated. In notation, H_0: $\rho=0$ against H_1: $\rho\neq0$. For example since the p-value is small, we have enough evidence against the null hypothesis hence we conclude that the correlation between Percentage of removal and anode solution is significant. In statistical hypothesis testing, the p-value is the probability of obtaining a result at least as extreme as that obtained, assuming the truth of the null hypothesis that the finding was the result of chance alone. The fact that p-values are based on this assumption is crucial to their correct interpretation. More technically, the p-value of an observed value of some random variable T used as a test statistic is the probability that, given that the null hypothesis is true, T will assume a value as or more unfavorable to the null hypothesis as the observed value. "More unfavorable to the null hypothesis" can in some cases mean greater than, in some cases less than, and in some cases further away from a specified center. Critics of p-values point out that the criterion used to decide "statistical significance" is based on the somewhat arbitrary choice of level (often set at 0.05).

6.8.2 Bivariate EDA – Scatterplot/Partial Regression Plots

The smaller the variability of the residual values around the regression line relative to the overall variability, the better is our prediction. For example, if there is no relationship between the X and Y variables, then the ratio of the residual variability of the Y variable to the original variance is equal to 1.0. If X and Y are perfectly related then there is no residual variance and the ratio of variance would be 0.0. In most cases, the ratio would fall somewhere between these extremes, that is, between 0.0 and 1.0. 1.0 minus this ratio is referred to as R-square or the coefficient of determination. This value is immediately interpretable in the following manner. If we have an R-square of 0.4 then we know that the variability of the Y values around the regression line is 1-0.4 times the original variance; in other words we have explained 40% of the original variability, and are left with 60% residual variability. Ideally, we would like to explain most if not all of the original variability. The R-square value is an indicator of how well the model fits the data (e.g., an R-square close to 1.0 indicates that we have accounted for almost all of the variability with the variables specified in the model). Figure 6.3 to 6.6 show the scatter plot for various input parameter versus the output parameter to study the variability statistics of the parameters.

Table 6.5 Descriptive Statistics for Scaled Variables

Variable	**Parameter**						
	N	**Range**	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**	**Variance**
Percentage of removal (Output_1)	96	0.570	0.328	0.898	0.747	0.109	0.012
Initial Concentration (Input_1)	96	0.375	0.375	0.750	0.559	0.160	0.026
Anode Solution (Input_2)	96	0.600	0.150	0.750	0.236	0.155	0.024
Conc. Of Anode (Input_3)	96	0.684	0.316	1.000	0.950	0.179	0.032
Cathode Solution (Input_4)	96	0.600	0.150	0.750	0.228	0.147	0.022
Conc. Of Cathode (Input_5)	96	0.684	0.316	1.000	0.466	0.284	0.081
Voltage Applied (Input_6)	96	0.583	0.167	0.750	0.472	0.152	0.023
Current (Input_7)	96	0.412	0.174	0.586	0.386	0.081	0.007
Current Density (Input_8)	96	0.301	0.441	0.742	0.604	0.051	0.003
Ambient Temperature (Input_9)	96	0.268	0.474	0.742	0.628	0.086	0.007
Temp. Anode (Input_10)	96	0.477	0.347	0.824	0.506	0.099	0.010
Temp. Center (Input_11)	96	0.383	0.354	0.737	0.507	0.086	0.007
Temp. Cathode (Input_12)	96	0.312	0.353	0.665	0.500	0.077	0.006
Voltage Anode (Input_13)	96	0.534	0.157	0.690	0.322	0.115	0.013
Voltage Center (Input_14)	96	0.527	0.216	0.743	0.434	0.122	0.015
Voltage Cathode (Input_15)	96	0.510	0.317	0.827	0.551	0.145	0.021
Length of Sample (Input_16)	96	0.380	0.230	0.610	0.273	0.104	0.011
Cross Sectional Area (Input_17)	96	0.608	0.203	0.811	0.260	0.178	0.032

Table 6.6 Correlation Coefficient and p values

Independent variables	Correlation Coefficients	p-value
Initial Concentration	-0.090	3.810E-01
Anode Solution	-0.771	3.915E-20*
Conc. Of Anode	0.079	4.420E-01
Cathode Solution	-0.020	8.500E-01
Conc. Of Cathode	-0.200	5.100E-02
Voltage Applied	0.109	2.900E-01
Current	-0.390	8.475E-5*
Current Density	-0.234	0.022*
Ambient Temperature	-0.050	6.310E-01
Temp. Anode	0.241	0.018*
Temp. Center	0.185	7.200E-02
Temp. Cathode	0.047	6.480E-01
Voltage Anode	0.315	0.002*
Voltage Center	0.519	6.069E-8*
Voltage Cathode	0.473	1.109E-6*
Length of Sample	0.014	8.920E-01
Cross Sectional Area	0.125	2.250E-01

Level of significance: 5%

*The highlighted values represents that the correlation is significant.

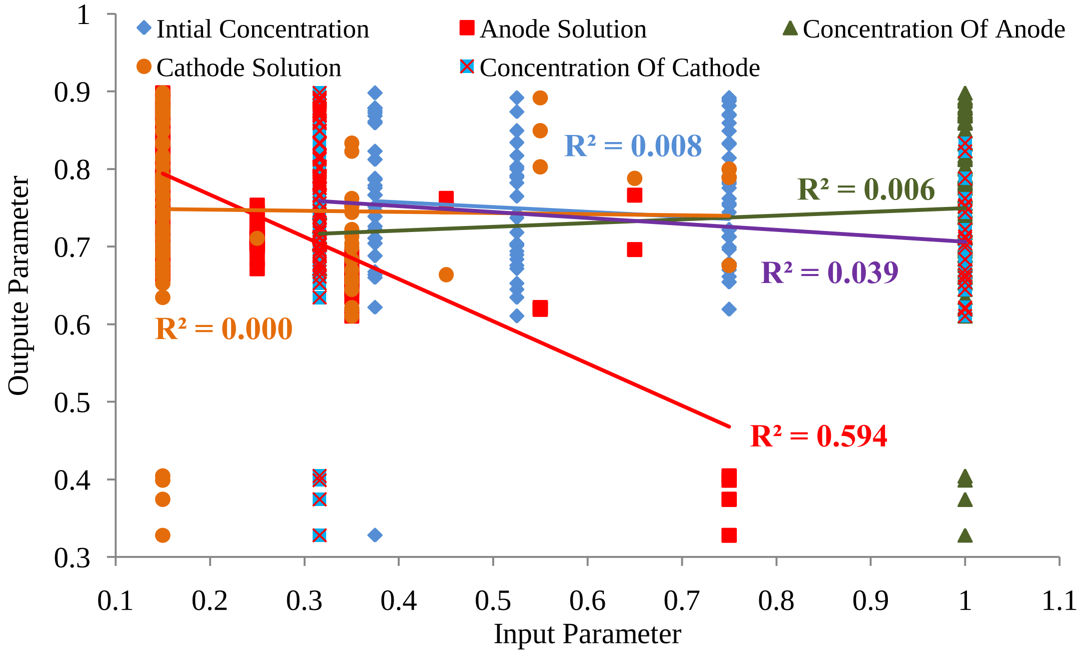


Fig. 6.3 Bivariate EDA – Scatterplot for Electrokinetic Removal of Nickel (Effect of Purging Solution and Its Concentration)

The simple linear regression of output % removal on initial concentration has an R^2 value of 0.008. i.e. it explains 0.8% variation in the output % removal. The simple linear regression of output % removal on anode solution and its concentration has an R^2 value of 0.0594 and 0.006 respectively i.e. it explains 5.94% and 0.6% variation in the output % removal. Similarly, the simple linear regression of output % removal on cathode solution and its concentration has an R^2 value of 0.000 and 0.039 respectively i.e. it explains 0% (actual R^2 = 3.84E-4) and 3.9% variation in the output % removal.

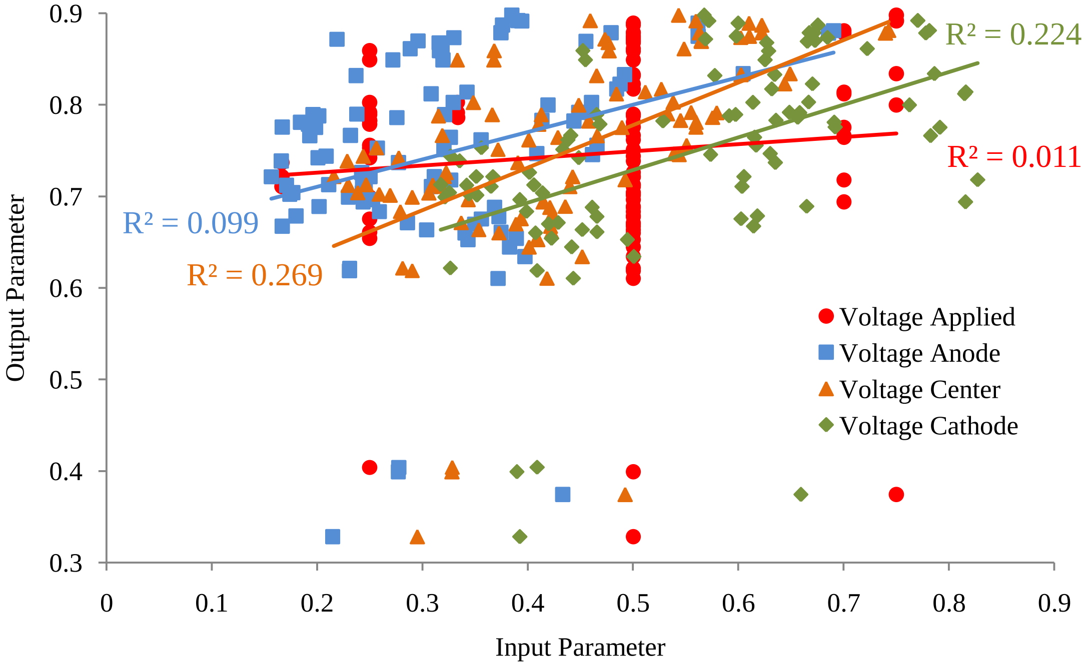


Fig. 6.4 Bivariate EDA – Scatterplot for Electrokinetic Removal of Nickel (Effect of Voltage Applied and Measured Voltage)

The simple linear regression of output % removal on voltage applied has an R^2 value of 0.011. i.e. it explains 1.1% variation in the output % removal whereas when looking into the measured voltage near anode region, at center and near cathode region the simple linear regression of output % removal on each has an R^2 value of 0.099, 0.269 and 0.224 respectively i.e. it explains 9.9%, 26.9% and 22.4% variation respectively in the output % removal.

The simple linear regression of output % removal on current and current density has an R^2 value of 0.152 and 0.054 respectively i.e. it explains 15.2% and 5.4% variation in the output % removal. Similarly taking into consideration the reactor dimensions i.e. length of sample and cross sectional area the simple linear regression of output % removal on has an R^2 value of 0.000 and 0.015 i.e. it explains 0% and 1.5% variation in the output % removal. The simple linear regression of output % removal on ambient temperature has an R^2 value of 0.002. i.e. it explains 0.2% variation in the output % removal on an similar line temperature measured near anode region, at the center and near the cathode region shows the simple linear regression with output % removal an R^2 value of 0.058, 0.034 and 0.002 respectively i.e. it explains 5.8%, 3.4% and 0.25 variation in the output % removal.

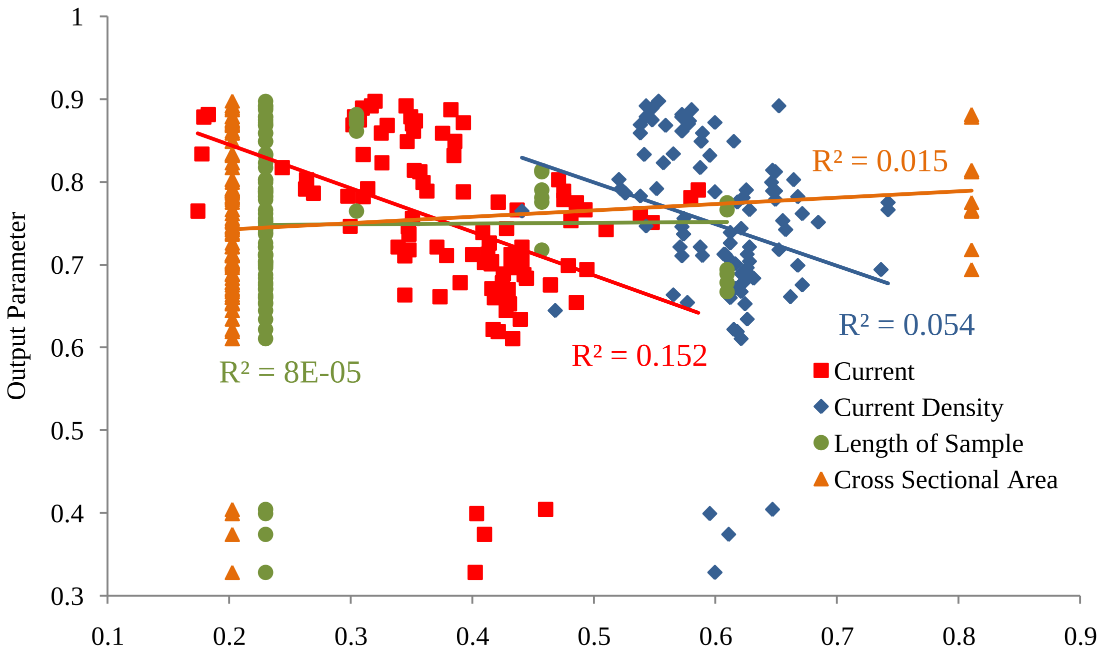


Fig.6.5 Bivariate EDA – Scatterplot for Electrokinetic Removal of Nickel (Effect of Current, Current Density and Reactor Dimensions)

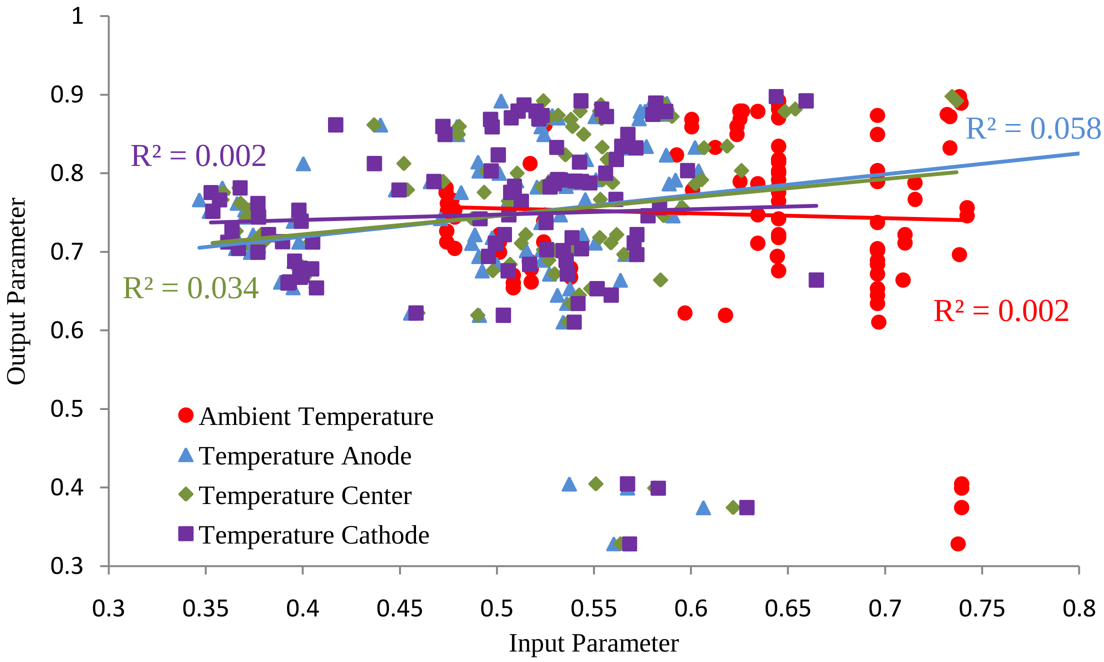


Fig. 6.6 Bivariate EDA – Scatterplot for Electrokinetic Removal of Nickel (Effect of Temperature)

6.8.3 Multiple Regression Analysis

Regression Analysis is one of the most widely used techniques for analyzing multifactor data, its broad appeal and usefulness results from the conceptually logical process of using an equation to express the relationship between a variable of interest (the response) and a set of related predictor variables. Successful use of regression requires an appreciation of both the theory and the practical problems that typically arise when the technique is employed with real-world data. A regression model that involves more than one regressor variable is called a Multiple Regression Model. Suppose the response y may be related to k regressor or predictor variables. The model

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots\ldots + \beta_k x_k + \varepsilon$$

is called a Multiple Linear Regression model with k regressors. The parameter β_j ; j=0,1,…k are called the regression coefficients. The parameters β_j represents the expected change in the response variable y per unit change in x_j when all of the remaining regressor variable x_i ($i \neq j$) are held constant. For this reason the parameters β_j ; j=0,1,…k are often called partial regression coefficients. Models that include interaction effects may also be analyzed by Multiple Linear regression methods. Let us take

y= Percentage of removal
x_1=Initial Concentration
x_2=Anode Solution
x_3=Conc. Of Anode
x_4=Cathode Solution
x_5=Conc. Of Cathode
x_6=Voltage Applied
x_7=Current
x_8=Current Density
x_9=Ambient Temperature
x_{10}=Temp. Anode
x_{11}=Temp. Center
x_{12}=Temp. Cathode
x_{13}=Voltage Anode
x_{14}=Voltage Center
x_{15}=Voltage Cathode
x_{16}=Length of Sample
x_{17}=Cross Sectional Area

The regression model is

$$y = \beta_0 + \beta_i x_i + \varepsilon_i \qquad \text{where } i = 1,2,\ldots\ldots,17$$

6.8.4 Test for Significance of Regression

The test for significance of regression is a test to determine if there is a linear relationship between the response variable and any of the regressor variables. This procedure is often thought of as on overall or global test of model adequacy. The appropriate hypotheses are Ho: $\beta_1=\beta_2=\ldots\ldots=\beta_k=0$ against H_1: $\beta_j \neq 0$ for at least one j. Since the ***p-value*** (Table 6.7 & 6.8) is small, we have enough evidence against the null hypothesis hence we conclude that the regression model is significant, that is the percentage of removal not related to any of the regressor variables.

6.8.5 Tests on Individual Regression Coefficients

Hypothesis: Ho: $\beta_j=0$ against H1: $\beta_j \neq 0$. Since the ***p-value*** is small, we have enough evidence against the null hypothesis hence we conclude that the regressor anode solution, voltage applied and length of sample contributes significantly to the model given than the other regressors in the model while the rest of the regressors do not contribute significantly to the model. The Fitted regression model is

$$y = 0.71+0.018x_1-0.536\,x_2+0.033x_3-0.051x_4+0.006x_5+0.175x_6+0.084x_7 +0.193x_8+0.137x_9+0.325x_{10}-0.055x_{11}-0.0608x_{12}-0.130x_{13}+0.211x_{14} +0.133x_{15}-0.507x_{16}-0.014x_{17}$$

Two ways to assess the overall adequacy of the model are R^2 and adjusted R^2. Since the value of R^2 is 0.758 that is 75.8% variation in the response variable is explained by this model, whereas the value of adjusted R^2 is 0.705, with standard error of the estimate equal to 0.0592. To construct confidence interval estimates for the regression coefficients βj we assume that the errors are normally and independently distributed with mean zero and variance σ2. Based on this a 100(1-α)% Confidence Intervals for the regression coefficients βj ; j=0,1,…k (Table 6.9). Table 6.10 shows the residual statistics for the model. A 100(1-α) percent confidence interval on the regression coefficient, βj, is obtained as follows:

$$\beta_j = \widehat{\beta_j} \pm t_{\alpha/2,n-(k+1)}\sqrt{C_{jj}}$$

Table 6.7 Hypothesis Analysis

Model	Sum of Squares	Df	Mean Square	F	p-value
Regression	0.858	17	0.050	14.384	1.589E-17
Residual	0.274	78	0.004		
Total	1.132	95			

Table 6.8 Confidence Intervals of the Regression Coefficients

Variable	Unstandardized Coefficients		Standardized Coefficients Beta	t statistics	p-value
	β	Standard Error			
(Constant)	0.710	0.136	-	5.228	1.398E-6
Initial Concentration	0.018	0.040	0.026	0.442	0.660
Anode Solution	-0.536	0.053	-0.759	-10.057	9.819E-16
Conc. Of Anode	0.033	0.039	0.054	0.844	0.401
Cathode Solution	-0.051	0.080	-0.069	-0.641	0.524
Conc. Of Cathode	0.006	0.037	0.015	0.152	0.880
Voltage Applied	0.175	0.056	0.244	3.152	0.002
Current	0.084	0.167	0.062	0.503	0.616
Current Density	0.193	0.216	0.089	0.890	0.376
Ambient Temperature	0.137	0.298	0.108	0.461	0.646
Temp. Anode	0.325	0.290	0.296	1.121	0.266
Temp. Center	-0.055	0.565	-0.043	-0.097	0.923
Temp. Cathode	-0.608	0.485	-0.430	-1.253	0.214
Voltage Anode	-0.130	0.129	-0.137	-1.004	0.318
Voltage Center	0.211	0.194	0.236	1.085	0.281
Voltage Cathode	0.133	0.162	0.177	0.825	0.412
Length of Sample	-0.507	0.126	-0.485	-4.017	1.346E-4
Cross Sectional Area	-0.014	0.059	-0.023	-0.234	0.816

Table 6.9 95% Confidence Interval for β

Variable	Lower Bound	Upper Bound
(Constant)	0.44	0.98
Initial Concentration	-0.062	0.097
Anode Solution	-0.642	-0.43
Conc. Of Anode	-0.045	0.111
Cathode Solution	-0.211	0.108
Conc. Of Cathode	-0.068	0.079
Voltage Applied	0.065	0.286
Current	-0.248	0.416
Current Density	-0.238	0.623
Ambient Temperature	-0.456	0.73
Temp. Anode	-0.252	0.901
Temp. Center	-1.179	1.07
Temp. Cathode	-1.573	0.358
Voltage Anode	-0.387	0.127
Voltage Center	-0.176	0.598
Voltage Cathode	-0.188	0.455
Length of Sample	-0.759	-0.256
Cross Sectional Area	-0.131	0.104

Table 6.10 Residuals Statistics

	Minimum	Maximum	Mean	Std. Deviation
Predicted Value	4.25E-01	9.05E-01	7.47E-01	9.50E-02
Residual	-1.56E-02	2.45E-01	0.00E+00	5.37E-02
Std. Predicted Value	-3.39E+00	1.66E+00	0.00E+00	1.00E+00
Std. Residual	-2.63E+00	4.14E+00	0.00E+00	9.06E-01

6.8.6 Assumption Checking

Once the regression model has been identified it needs to be check whether the assumption used for its generation are valid or not. The major assumptions made in the study of Regression Analysis are as follows:

- The errors are normally and independently distributed with mean 0 and variance σ^2.
- The errors are uncorrelated.

For validity of these assumptions the residual analysis using the normal probability plot and the plot of residuals versus the fitted values $\hat{y}_i$ has been performed as shown in the Figures 6.7 to 6.9. The distribution of variables has been examined using a histogram. For the model to be used the shape of the distribution should be symmetrical bell shaped distribution, any skew in the data will produce the output value to be skewed also. If the residuals turn out to be non-normal, one needs to transform the output to obtain a normal distribution of the output.

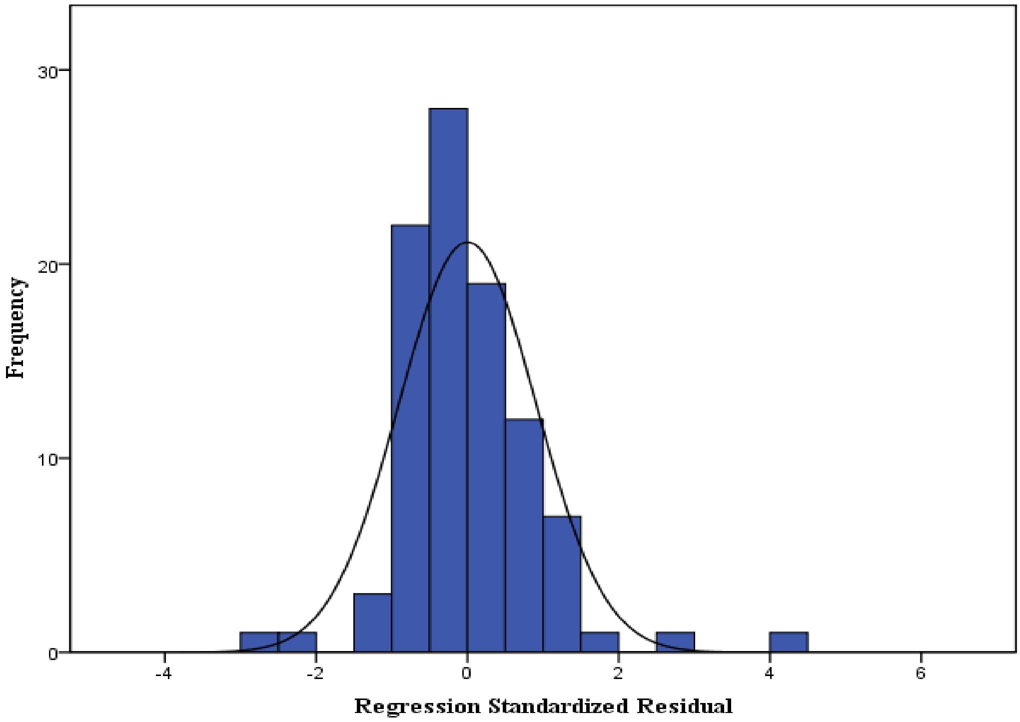


Fig. 6.7 Histogram Dependent Variable : Output % Removal
(Mean = 2.06E-15, Standard Deviation =0.906)

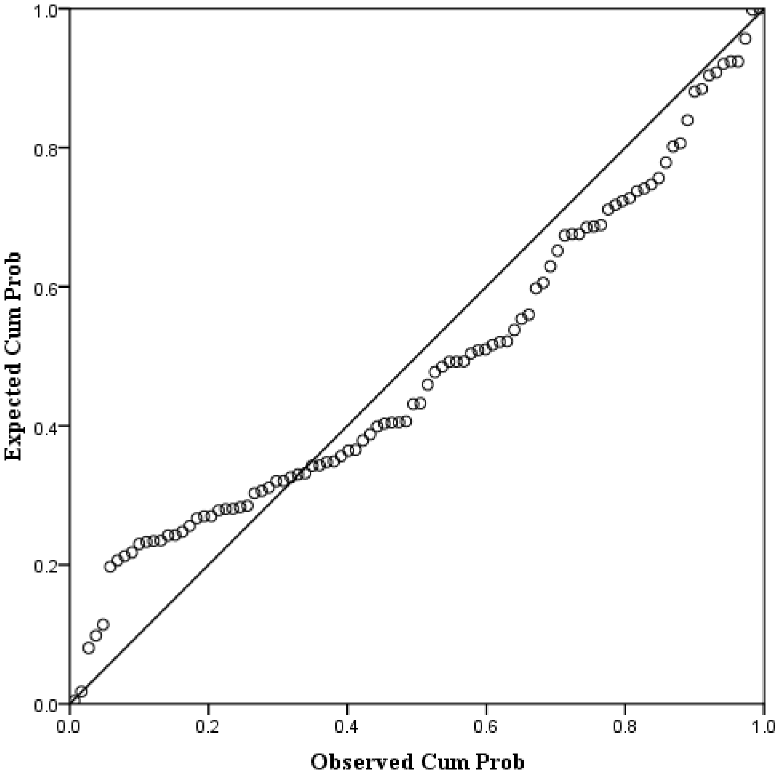


Fig. 6.8 Normal P – P Plot of Regression Standardized Residual
Dependent Variable : Output % Removal

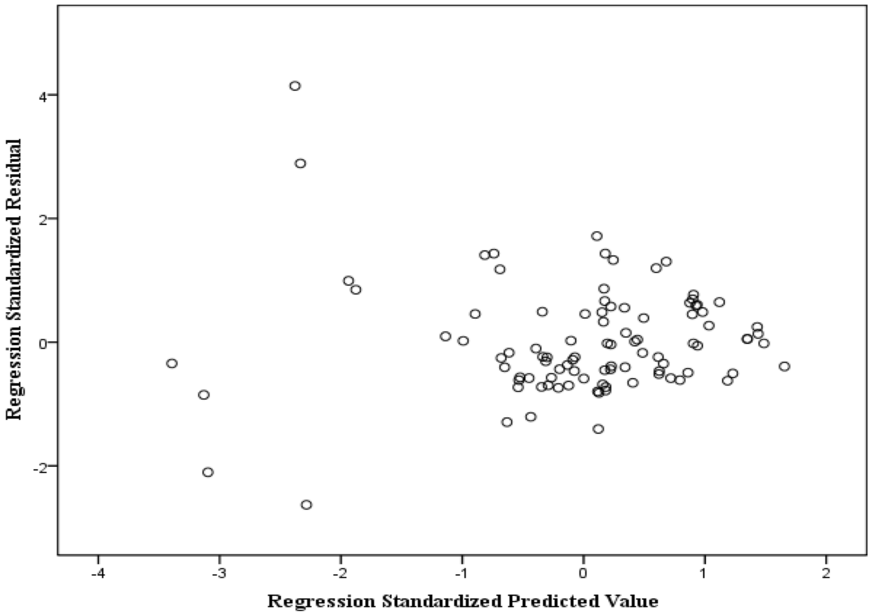


Fig. 6.9 Scatterplot: Dependent Variable : Output % Removal

6.9 REGRESSION MODEL FOR ELECTROKINETIC GROUTING

Grouting as a procedure for ground improvement is carried out with two aims in mind wherein one of them takes more importance over the other depending on the site condition and the future use or the purpose/need of improvement as intended. The two basic aims of grouting intend to either decrease the permeability of the soil layer to be grouted alongwith some increase in the strength or the other way round where the principal plan is to increase a given soil strength to higher level as aimed for.

6.9.1 Bivariate EDA Correlation Analysis

Keeping this in mind for field applications of grouting, the regression analysis was therefore carried out in two ways first with the increase in shear strength (Model UCS) as the output parameter and the other decrease in permeability (Model k) being kept as the output parameter. The selected variables were such that they included effects of other variables into themselves. Current density has been included since it included the effect of the size of reactor i.e. the cross sectional area. Current and current density together took care of the initial water content since it shall affect the resistance of the soil thereby the current flow in the soil throughout the experimental duration. Voltage applied has been taken as a variable instead of voltage gradient so as to include the effect of length of the reactor. Ambient temperature was included so as to take care of the temperature effect as well as the amount of moisture loss from the surface of the reactor. Looking into the wide variation of values over for the different variables as is apparent from Table 6.11, scaling of variables was carried out for Electrokinetic Grouting data too. Table 6.12 gives the details of the scaling factors for the parameter involved in electrokinetic grouting. Table 6.14 gives the statistical analysis of the scaled down variables. The decrease in the variation is of utmost importance so as to get a reliable regression model. This reasoning is supported by values as shown in Table 6.15 and 6.16, which shows the correlation analysis as well as p scale values for each of the independent variables for Model UCS and Model k. The null hypothesis has been used considering 5% significance level for each of the variables with respect to the output values for respective regression model.

6.9.2 Bivariate EDA – Scatterplot/Partial Regression Plots

The simple linear regression of output parameter i.e. % UCS Increase (Model UCS) and % Permeability Decrease (Model k) on the type of soil has an R^2 value of 0.145 and 0.194 respectively i.e. it explains 14.5% and 19.4% variation in output parameter (Fig. 6.10). On the same base, the simple linear regression of output parameter i.e. % UCS Increase (Model UCS) and % Permeability Decrease (Model k) on the concentration of anode solution i.e. the reactant used for the grout to gellify which in our case is Calcium Chloride has an R^2 value of 0.107 and 0.005 respectively i.e. it explains 10.7% and 0.5% variation in output parameter (Fig. 6.11).

When looking on the plot for the simple linear regression of output parameter i.e. % UCS Increase (Model UCS) and % Permeability Decrease (Model k) on the concentration of cathode solution i.e. the grout base used which in the present study is Sodium Silicate has an R^2 value of 0.144 and 0.076 respectively i.e. it explains 14.4% and 7.6% variation in output parameter (Fig. 6.12).

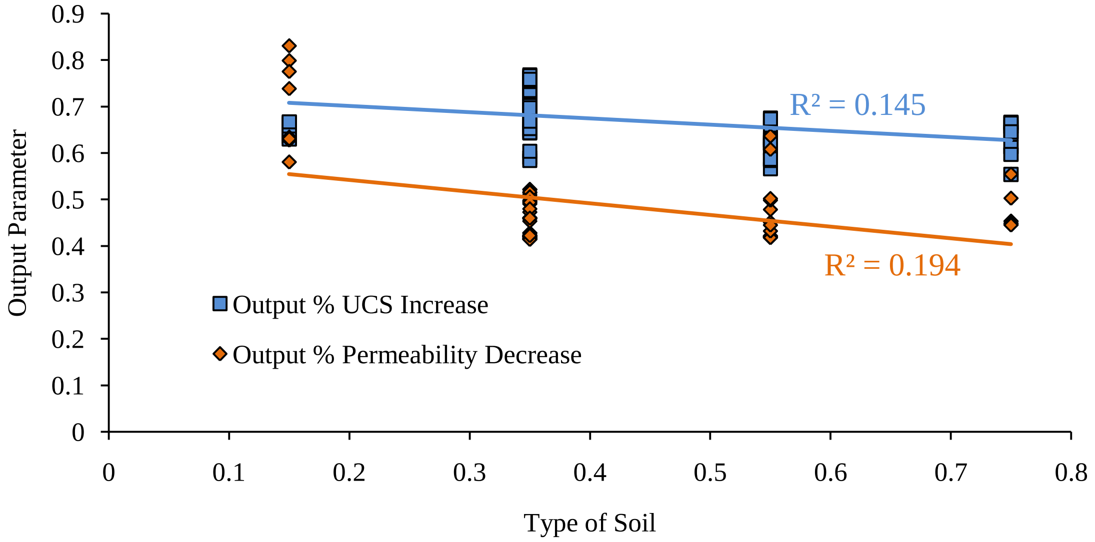


Fig. 6.10 Bivariate EDA – Scatterplot for Electrokinetic Grouting Model UCS and Model k (Effect of Soil Type)

The plot for the simple linear regression of output parameter i.e. % UCS Increase (Model UCS) and % Permeability Decrease (Model k) on the voltage applied has an R^2 value of 0.053 and 0.017 respectively i.e. it explains 5.3% and 1.7% variation in output parameter (Fig. 6.13). The values all lie on the same vertical line since voltage applied was in relation to the length of the reactor i.e. the distance between the cathode electrode and the anode electrode.

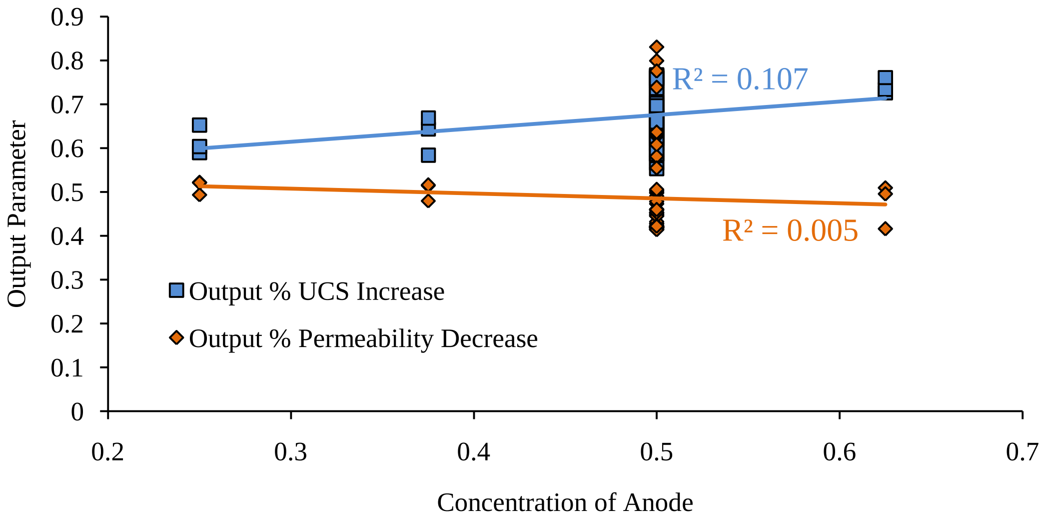


Fig. 6.11 Bivariate EDA – Scatterplot for Electrokinetic Grouting Model UCS and Model k (Effect of Concentration of Anode)

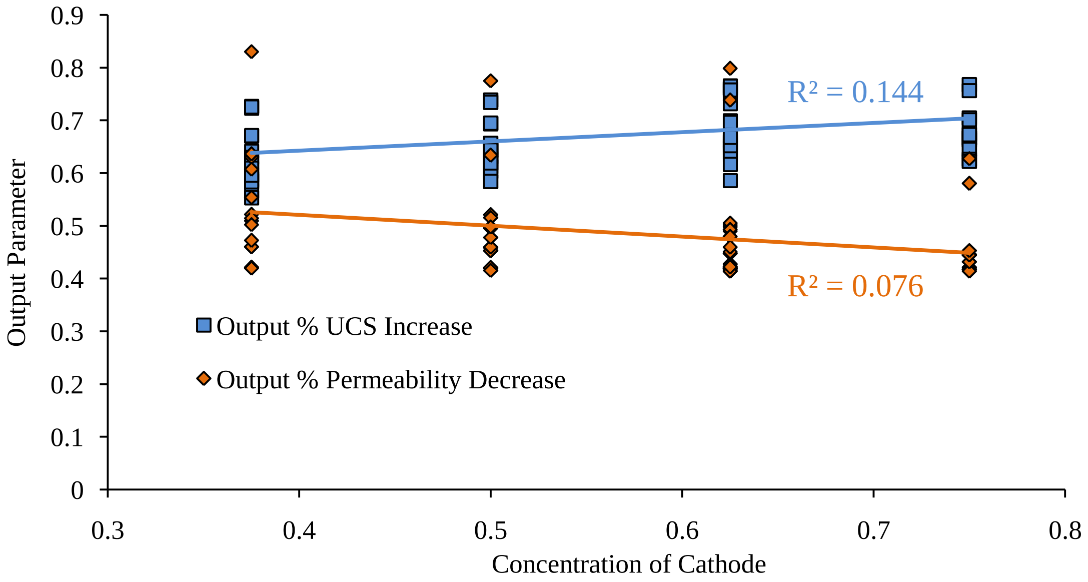


Fig. 6.12 Bivariate EDA – Scatterplot for Electrokinetic Grouting Model UCS and Model k (Effect of Concentration of Cathode)

Similarly, the plot for the simple linear regression of output parameter i.e. % UCS Increase (Model UCS) and % Permeability Decrease (Model k) on the current has an R^2 value of 0.044 and 0.060 respectively i.e. it explains 4.4% and 6.0% variation in output parameter (Fig. 6.14). The current value shows the points to be clustered in an area since the major comparative work for various factors affecting the process of electrokinetic grouting was studied on a single soil at an given water content which produced a resistance of soil of similar magnitude.

Table 6.11 List of Variable and Descriptive Statistics (Unscaled Values)

Code Name	Variable	Parameter						
		N	Range	Minimum	Maximum	Mean	Standard Deviation	Variance
Common Input Variable for Percentage Permeability Decrease Model & Percentage UCS Increase Model								
Input 1	Type of Soil	68	Qualitative Value					
Input 2	Conc. Of Anode	68	1.500	1.000	2.500	2.000	0.000	0.000
Input 3	Conc. Of Cathode	68	15.000	15.000	30.000	25.000	0.000	0.000
Input 4	Voltage Applied	68	25.000	12.500	37.500	18.750	8.839	78.125
Input 5	Current	68	1.21E-01	4.90E-02	1.70E-01	1.42E-01	3.90E-02	2.00E-03
Input 6	Current Density	68	2.80E-04	1.42E-05	2.94E-04	2.41E-04	6.01E-05	3.61E-09
Input 7	Ambient Temperature	68	9.157	26.123	35.280	26.899	0.297	0.088
Input 8	No. of days	68	42.000	35.000	77.000	45.500	14.849	220.500
Input 9	pH of Soil	68	7.00E-01	7.90E+00	8.60E+00	8.55E+00	7.10E-02	5.00E-03
Output % UCS Increase Regression Model (Model UCS)								
Input 10	Permeability	68	1.98E-02	1.28E-07	1.98E-02	7.54E-07	8.85E-07	7.83E-13
Output 1	Output % UCS Increase	68	211.591	16.818	228.409	127.744	101.865	10376.417
Output % Permeability Decrease Regression Model (Model k)								
Input 10	UCS	68	7.80E-02	7.00E-02	1.48E-01	7.90E-02	1.27E-02	1.62E-04
Output 2	Output % Permeability Decrease	68	84.224	0.703	84.928	39.202	54.007	2916.804

Table 6.12 Scaling Factors for Input and Output Variables for Electrokinetic Grouting

Quantity	Scaling Factor
Type of Soil (TS)	As per Table 6.13
Conc. Of Anode (CA)	= CA/10*2.5
Conc. Of Cathode (CC)	= CC/40
Voltage Applied (V)	= V/50
Current (C)	=SQRT(C)*1.5
Current Density (CD)	=(SQRT((LOG(CD))*-0.1))
Ambient Temperature (AT)	= AT/40
No. of days (ND)	=ND/100
pH of Soil (pH)	=pH/15
Initial UCS (IU)	=SQRT(IU)*2
Initial Permeability (IP)	=(SQRT((LOG(IP))*-0.1))
Output % UCS Increase (OU)	=(SQRT(LOG(OU)))/2
Output % Permeability Decrease (OP)	=((LOG(SQRT(OP)/100))*-1)/2.5

Table 6.13 Scaling Factor for Qualitative Input Parameters

Soil Type	Black Cotton Soil	Yellow Soil	Sandy Silt	Dahej Soil
Scaled Value	0.15	0.35	0.55	0.75

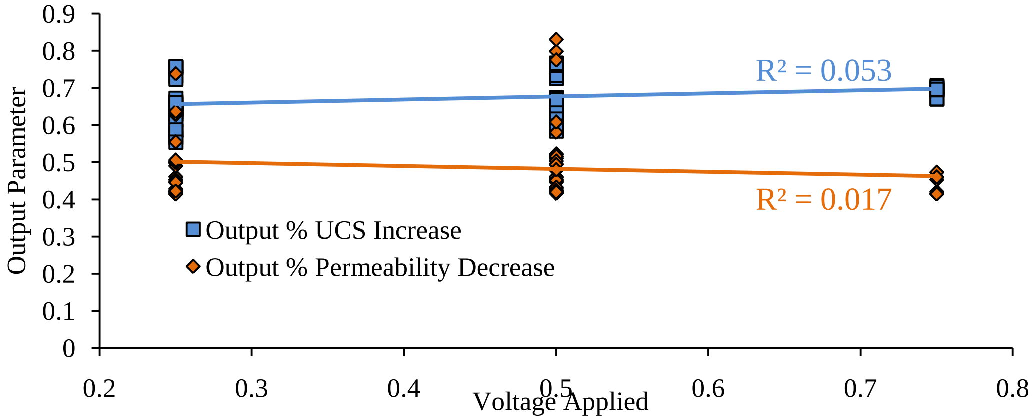


Fig. 6.13 Bivariate EDA – Scatterplot for Electrokinetic Grouting Model UCS and Model k (Effect of Voltage Applied)

Figure 6.15 shows the plot for the simple linear regression of output parameter i.e. % UCS Increase (Model UCS) and % Permeability Decrease (Model k) on current density has an R^2 value of 3E-05 and 0.003 respectively i.e. it explains 0.003% and 0.3% variation in output parameter. The simple linear regression of output parameter i.e. % UCS Increase (Model UCS) and % Permeability Decrease (Model k) on the ambient temperature has an R^2 value of 0.015 and 0.098 respectively i.e. it explains 1.5% and 9.8% variation in output parameter (Fig. 6.16). This factor has been considered in the model to take into account any surface drying taking place of the soil due to evaporation from the surface even though the soil in the reactor was always covered with a moist muslin cloth at all times.

Table 6.14 List of Variable and Descriptive Statistics (Scaled Values)

Variable	Parameter						
	N	Range	Minimum	Maximum	Mean	Standard Deviation	Variance
Common Input Variable for Percentage Permeability Decrease Model & Percentage UCS Increase Model							
Type of Soil	68	0.600	0.150	0.750	0.421	0.168	0.028
Conc. Of Anode	68	0.375	0.250	0.625	0.489	0.064	0.004
Conc. Of Cathode	68	0.375	0.375	0.750	0.566	0.129	0.017
Voltage Applied	68	0.500	0.250	0.750	0.438	0.164	0.027
Current	68	0.286	0.332	0.618	0.491	0.043	0.002
Current Density	68	0.102	0.594	0.696	0.613	0.017	0.000
Ambient Temperature	68	0.229	0.653	0.882	0.734	0.086	0.007
No. of days	68	0.420	0.350	0.770	0.414	0.128	0.016
pH of Soil	68	0.047	0.527	0.573	0.562	0.016	0.000
Percentage UCS Increase Model (Model UCS)							
Permeability	68	0.418	0.413	0.830	0.687	0.139	0.019
Output % UCS Increase	68	0.214	0.554	0.768	0.672	0.059	0.004
Percentage Permeability Decrease Model (Model k)							
UCS	68	0.240	0.529	0.769	0.630	0.074	0.006
Output % Permeability Decrease	68	0.416	0.414	0.831	0.487	0.096	0.009

Table 6.15 Correlation coefficient and p Values for Model UCS

Independent variables	Correlation coefficients	p-value
Type of Soil	-0.381	0.001
Conc. Of Anode	0.328	0.006
Conc. Of Cathode	0.380	0.001
Voltage Applied	0.231	0.058
Current	-0.211	0.084
Current Density	0.005	0.965
Ambient Temperature	-0.126	0.307
No. of days	0.344	0.004
pH of Soil	0.490	2.208E-5
Permeability	0.462	7.220E-5

Table 6.16 Correlation coefficient and p Values for Model k
(Level of Significance = 5%)

Independent variables	Correlation coefficients	p-value
Type of Soil	-0.441	8.465E-05
Conc. Of Anode	-0.073	0.276
Conc. Of Cathode	-0.277	0.011
Voltage Applied	-0.134	0.138
Current	0.247	0.021
Current Density	-0.060	0.315
Ambient Temperature	-0.314	0.005
No. of days	-0.260	0.016
pH of Soil	0.073	0.277
UCS	-0.292	0.008

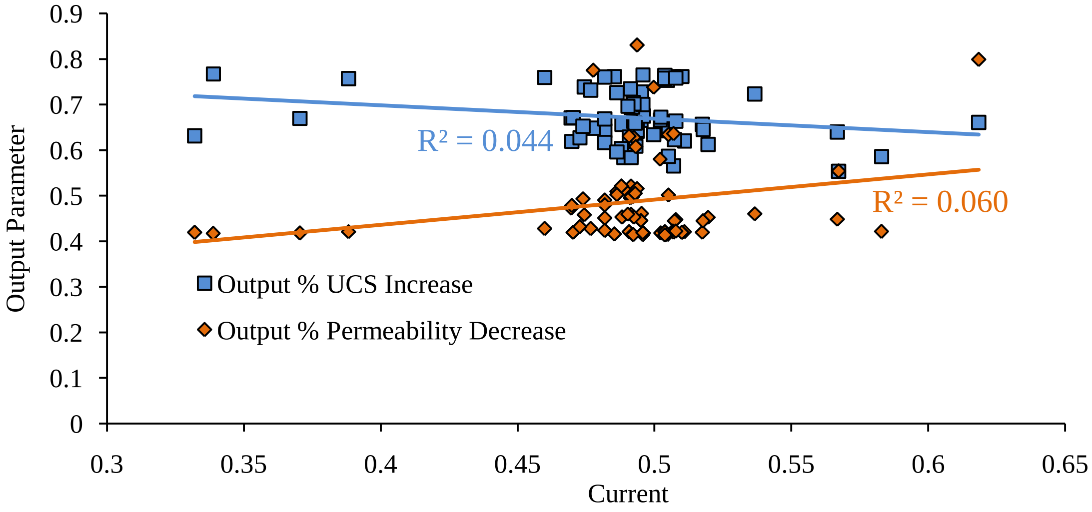


Fig. 6.14 Bivariate EDA – Scatterplot for Electrokinetic Grouting Model UCS and Model k (Effect of Current)

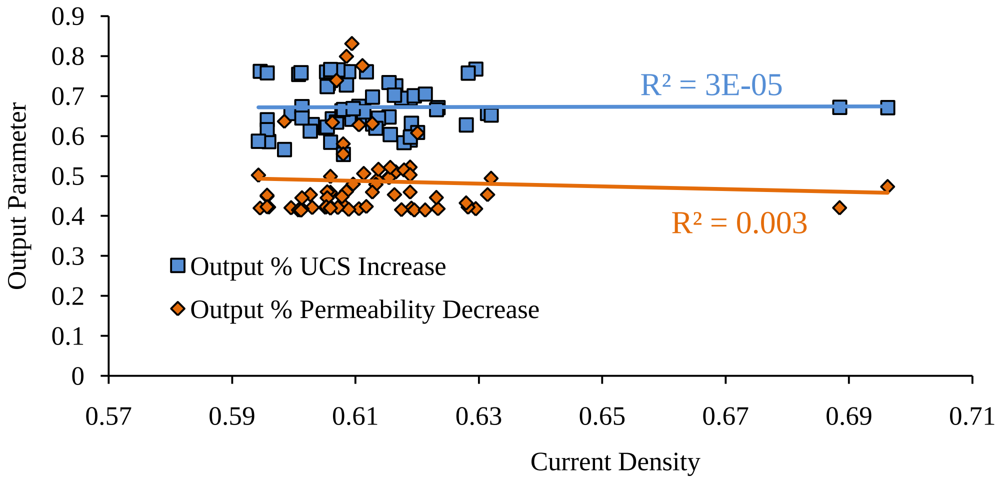


Fig. 6.15 Bivariate EDA – Scatterplot for Electrokinetic Grouting Model UCS and Model k (Effect of Current Density)

When looking on the plot for the simple linear regression of output parameter i.e. % UCS Increase (Model UCS) and % Permeability Decrease (Model k) on the experimental duration has an R^2 value of 0.118 and 0.067 respectively i.e. it explains 11.8% and 6.7% variation in output parameter (Fig. 6.17). The simple linear regression of output parameter i.e. % UCS Increase (Model UCS) and % Permeability Decrease (Model k) on the pH of soil has an R^2 value of 0.240 and 0.005 respectively i.e. it explains 24.0% and 0.5% variation in output parameter (Fig. 6.18).

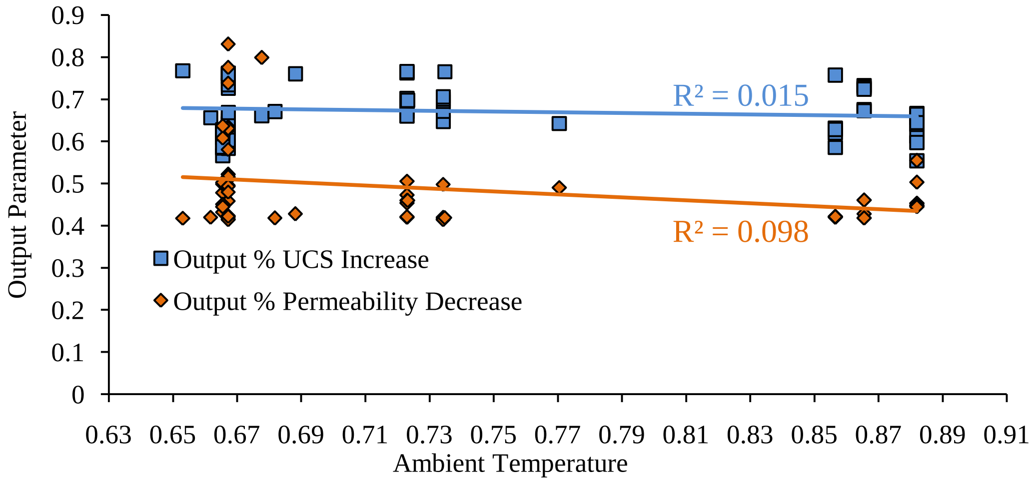


Fig. 6.16 Bivariate EDA – Scatterplot for Electrokinetic Grouting Model UCS and Model k (Effect of Ambient Temperature)

6.9.3 Multiple Regression Model

For the two models i.e. the Percentage increase in UCS model (Model UCS) and Percentage permeability decrease model (Model k) the list of variable has been as mentioned in Table 6.14 and the regression model fitted for the same is as per equation below:

$$y = \beta_0 + \beta_i x_i + \varepsilon_i \qquad i=1, 2, \ldots\ldots, 10$$

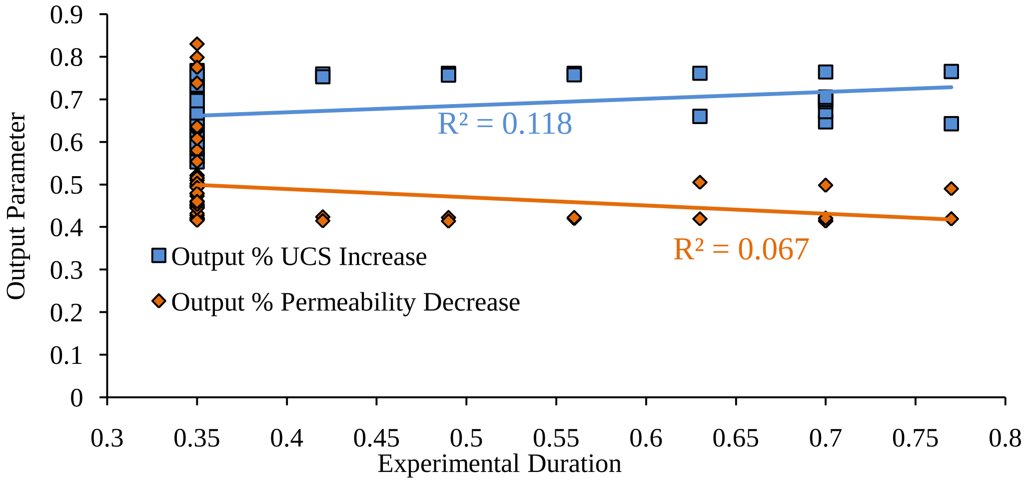


Fig. 6.17 Bivariate EDA – Scatterplot for Electrokinetic Grouting Model UCS and Model k (Effect of Experimental Duration)

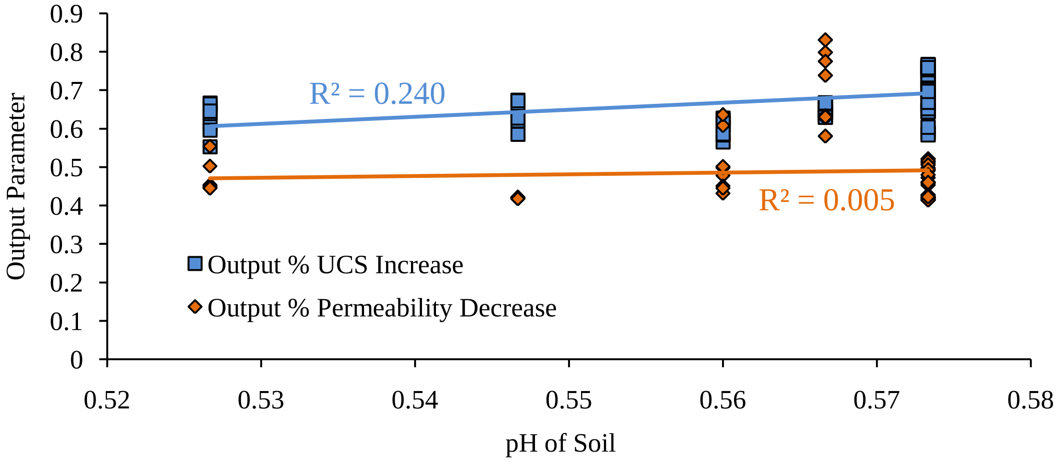


Fig. 6.18 Bivariate EDA – Scatterplot for Electrokinetic Grouting Model UCS and Model k (Effect of Soil pH)

6.9.4 Test for Significance of Regression

The test for significance of regression is a test to determine if there is a linear relationship between the response variable and any of the regressor variables. This procedure is often thought of as on overall or global test of model adequacy. The appropriate hypotheses are Ho: $\beta_1=\beta_2=\ldots\ldots=\beta_k=0$ against H_1: $\beta_j\neq0$ for at least one j. Since the ***p-value*** (Table 6.16, 6.17 and 6.18) is small, we have enough evidence against the null hypothesis hence we conclude that the regression model is significant, that is the percentage UCS increase and percentage permeability decrease are not related to any of the regressor variables.

6.9.5 Tests on Individual Regression Coefficients

Table 6.18 gives the confidence intervals for each of the regression coefficients generated for Model UCS. It is seen that the ***p-value*** is small for each of the predictors considered, therefore we have enough evidence against the null hypothesis hence we conclude that the regressor Conc. of Anode, Conc. Of Cathode, pH of Soil, and Permeability contributes significantly to the model given that the other regressors in the model. The Fitted regression model UCS is

$$y = -0.933 + 0.120x_1 + 0.341x_2 + 0.136x_3 + 0.055x_4 - 0.237x_5 - 0.669x_6 + 0.194x_7 - 0.008x_8 + 2.763x_9 + 0.177x_{10}$$

Table 6.17 Hypothesis Analysis

Model	Sum of Squares	Df	Mean Square	F	p-value
Model UCS **Predictors:** (Constant), Type of Soil, Conc. Of Anode, Conc. Of Cathode, Voltage Applied, Current, Current Density, Ambient Temperature, Experimental Duration, Soil pH, Permeability **Dependent Variable:** Output % UCS Increase					
Regression	0.161	10	0.016	12.296	5.248E-11
Residual	0.075	57	0.001		
Total	0.235	67			
Model k Predictors: (Constant), Type of Soil, Conc. Of Anode, Conc. Of Cathode, Voltage Applied, Current, Current Density, Ambient Temperature, Experimental Duration, Soil pH, UCS Dependent Variable: Output % Permeability Decrease					
Regression	0.481	10	0.048	20.020	3.277E-15
Residual	0.137	57	0.002		
Total	0.618	67			

Table 6.18 Confidence Intervals of the Regression Coefficients (Model UCS)

Model	Unstandardized Coefficients		Standardized Coefficients	t	p-value
	β	Standard Error	Beta		
(Constant)	-0.933	0.479		-1.948	0.056
Type of Soil	0.12	0.059	0.341	2.032	0.047
Conc. Of Anode	0.341	0.072	0.367	4.756	1.39E-05
Conc. Of Cathode	0.136	0.037	0.295	3.653	0.001
Voltage Applied	0.055	0.033	0.152	1.666	0.101
Current	-0.237	0.122	-0.171	-1.939	0.057
Current Density	-0.669	0.348	-0.188	-1.922	0.06
Ambient Temperature	0.194	0.073	0.282	2.654	0.01
No. of days	-0.008	0.041	-0.018	-0.201	0.841
pH of Soil	2.763	0.635	0.736	4.351	5.68E-05
Permeability	0.177	0.048	0.414	3.712	4.69E-04

Table 6.19 Confidence Intervals of the Regression Coefficients (Model k)

Variable	Unstandardized Coefficients		Standardized Coefficients Beta	t	p-value
	β	Standard Error			
(Constant)	4.654	6.49E-01		7.168	1.67E-09
Type of Soil	-1.279	1.48E-01	-2.243	-8.654	5.70E-12
Conc. Of Anode	-0.156	9.90E-02	-0.104	-1.586	1.18E-01
Conc. Of Cathode	-0.173	5.00E-02	-0.232	-3.448	1.00E-03
Voltage Applied	-0.004	4.60E-02	-0.007	-0.091	9.28E-01
Current	0.275	1.62E-01	0.122	1.692	9.60E-02
Current Density	0.184	4.67E-01	0.032	0.394	6.95E-01
Ambient Temperature	-0.104	1.16E-01	-0.094	-0.896	3.74E-01
No. of days	-0.027	5.60E-02	-0.036	-0.488	6.28E-01
pH of Soil	-7.704	8.98E-01	-1.266	-8.574	7.71E-12
UCS	1.140	2.41E-01	0.881	4.728	1.53E-05

Two ways to assess the overall adequacy of the model are R, R^2 and adjusted R^2. Since the value of R is 0.882 i.e. 88.2% reliability, R^2 is 0.778 that is 77.8% variation in the response variable is explained by this model, whereas the value of adjusted R^2 is 0.740, with standard error of the estimate equal to 0.0490. To construct confidence interval estimates for the regression coefficients βj we assume that the errors are normally and independently distributed with mean zero and variance σ^2. Based on this a 100(1-α)% Confidence Intervals for the regression coefficients βj ; j=0,1,…k has been shown. (Table 6.20). Table 6.21 shows the residual statistics for the model.

For each of the regression predictors for Model k, the p-value is small, we have enough evidence against the null hypothesis hence we conclude that the regressor: Type of soil, Conc. Of Cathode, pH of Soil and UCS contribute significantly to the Model k given that the other regressors in the model while the rest of the regressors do not contribute significantly to the model. Also the constant contributes significantly to the model. (Table 6.19). The Fitted regression line for Model k is

$$y = 4.654 - 1.279x_1 - 0.156x_2 - 0.173x_3 - 0.004x_4 + 0.275x_5 + 0.184x_6 - 0.104x_7 - 0.027x_8 - 7.704x_9 + 1.140x_{10}$$

Two ways to assess the overall adequacy of the model are R, R^2 and adjusted R^2. Since the value of R is 0.827 i.e. 82.7% reliability, R^2 is 0.683 that is 68.3% variation in the response variable is explained by this model, whereas the value of adjusted R^2 is 0.628, with standard error of the estimate equal to 0.0362. To construct confidence interval estimates for the regression coefficients βj we assume that the errors are normally and independently distributed with mean zero and variance σ^2. Based on this a 100(1-α)% Confidence Intervals for the regression coefficients βj ; j=0,1,…k (Table 6.22). Table 6.23 shows the residual statistics for the model.

Table 6.20 Confidence Interval for β (Model UCS)

Variable	95% Confidence Interval for β	
	Lower Bound	Upper Bound
(Constant)	-1.893	.026
Type of Soil	.002	.238
Conc. Of Anode	.197	.484
Conc. Of Cathode	.061	.211
Voltage Applied	-.011	.121
Current	-.483	.008
Current Density	-1.367	.028
Ambient Temperature	.048	.340
No. of days	-.089	.073
pH of Soil	1.491	4.034
Permeability	.081	.272

Table 6.21 Residual Statistics for Model UCS

	Minimum	Maximum	Mean	Standard Deviation
Predicted Value	5.77E-01	7.65E-01	6.72E-01	4.90E-02
Residual	-7.21E-02	7.04E-02	0.00	3.34E-02
Standard Predicted Value	-1.94	1.89	0.00	1.00
Standard Residual	-1.99	1.95	0.00	0.92

6.9.6 Assumption Checking

With each independent variable added to the regression equation, the effects of less than perfect reliability on the strength of the relationship becomes more complex and the results of the analysis can become questionable. With addition of one independent variable with less than perfect reliability each succeeding variable entered has the opportunity to claim part of the error variance left over by the unreliable variable(s). The apportionment of the explained variance among the independent variables will thus be incorrect. The more independent variables added to the equation with low levels of reliability the greater the likelihood that the variance accounted for is not apportioned correctly. This gets increasingly complex as the number of variables in the equation grows. Several assumptions of multiple regression are “robust” to violation (e.g., normal distribution of errors), and others are fulfilled in the proper design of a study (e.g., independence of observations). Therefore the four assumption of linearity, reliability of measurement, homoscedasticity i.e. constant variance, and normality are to be checked. Of the above four assumptions, reliability of the measurement need not be discussed since the values input to the model are actual measured values and not data from data sets. The homoscedasticity can be checked by visual examination of a plot of the histogram frequency plot of regression standardized residual value (Fig. 6.19 and 6.20).

Table 6.22 95% Confidence Interval for β (Model k)

Variable	95% Confidence Interval for B	
	Lower Bound	Upper Bound
(Constant)	3.354	5.955
Type of Soil	-1.574	-.983
Conc. Of Anode	-.354	.041
Conc. Of Cathode	-.274	-.073
Voltage Applied	-.095	.087
Current	-.050	.600
Current Density	-.751	1.119
Ambient Temperature	-.337	.129
No. of days	-.139	.084
pH of Soil	-9.503	-5.904
UCS	.657	1.623

Table 6.23 Residual Statistics for Model UCS

	Minimum	Maximum	Mean	Standard Deviation
Predicted Value	0.381	0.725	0.487	0.085
Residual	-1.01E-01	1.07E-01	-1.11E-15	4.52E-02
Standard Predicted Value	-1.25	2.81	0.00	1.00
Standard Residual	-2.07	2.17	0.00	0.92

The histogram plot should show a uniform bell shape without any skew to the left or right. In case this is observed it necessities the modification of the input and output variables by further scaling to reduce the noise. The constancy of the expected and observed output values can be seen from Figure 6.21 and 6.22. Graphical analysis is much more effective in trying to detect patterns in the residuals than looking at the raw numbers. There are different types of plots that can be employed to check the different model assumptions. The plots used for this study are scatter plot of Residual standardized residual versus Regression Standardized Predicted Value as shown in Figure 6.23 and 6.24.

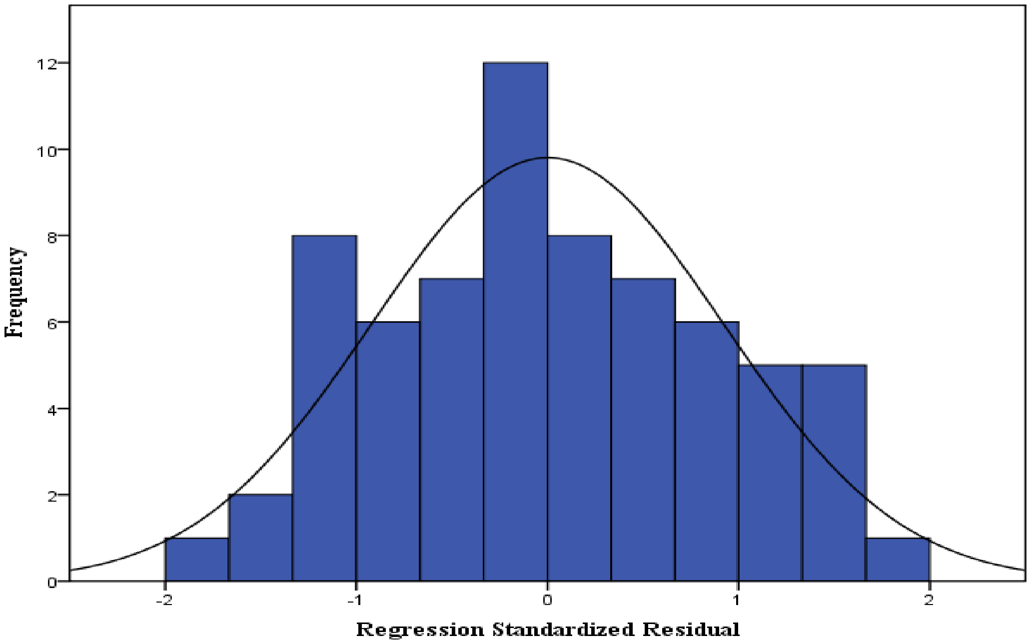


Fig. 6.19 Histogram Dependent Variable: Output % UCS Increase (Mean = 6.39E-15, Standard Deviation = 0.922)

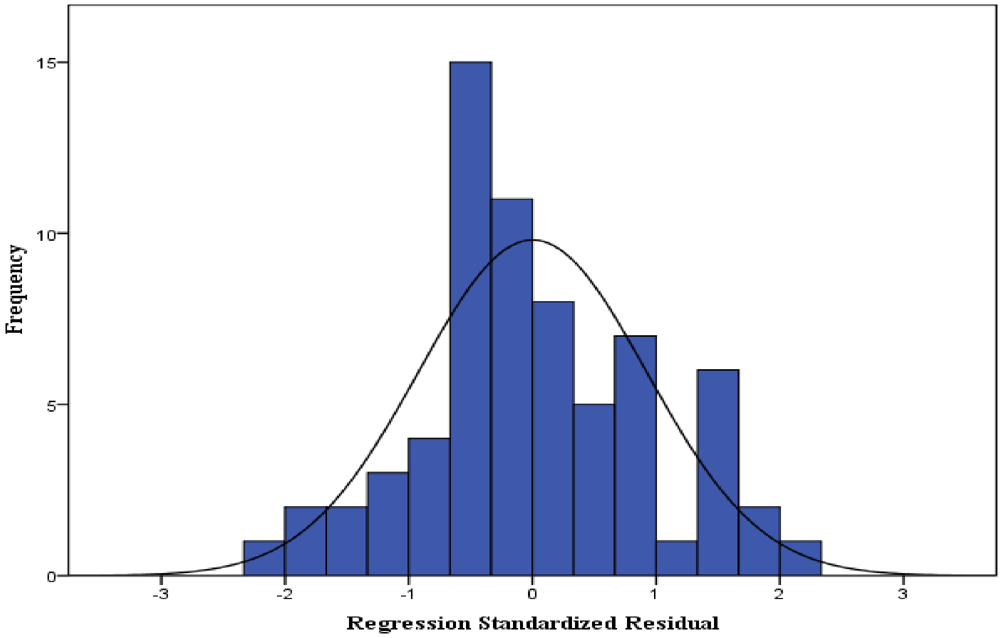


Fig. 6.20 Histogram Dependent Variable: Output % Permeability Decrease (Mean = 2.25E-14, Standard deviation = 0.922)

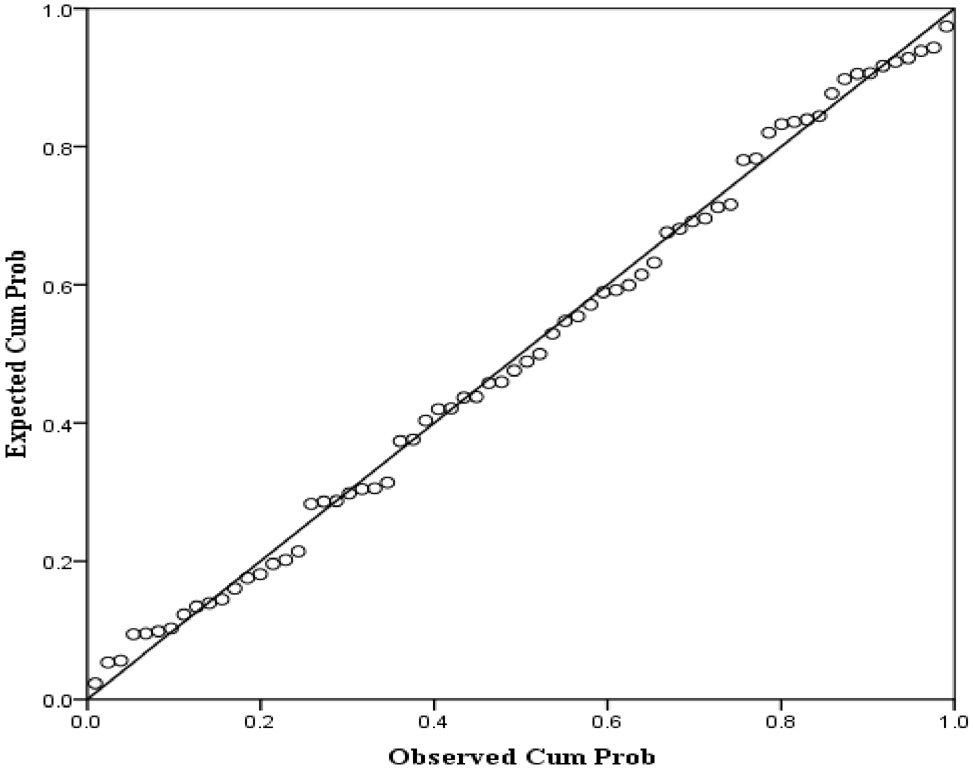


Fig. 6.21 Normal P – P Plot of Regression standardized Residual Dependent Variable: Output % UCS Increase

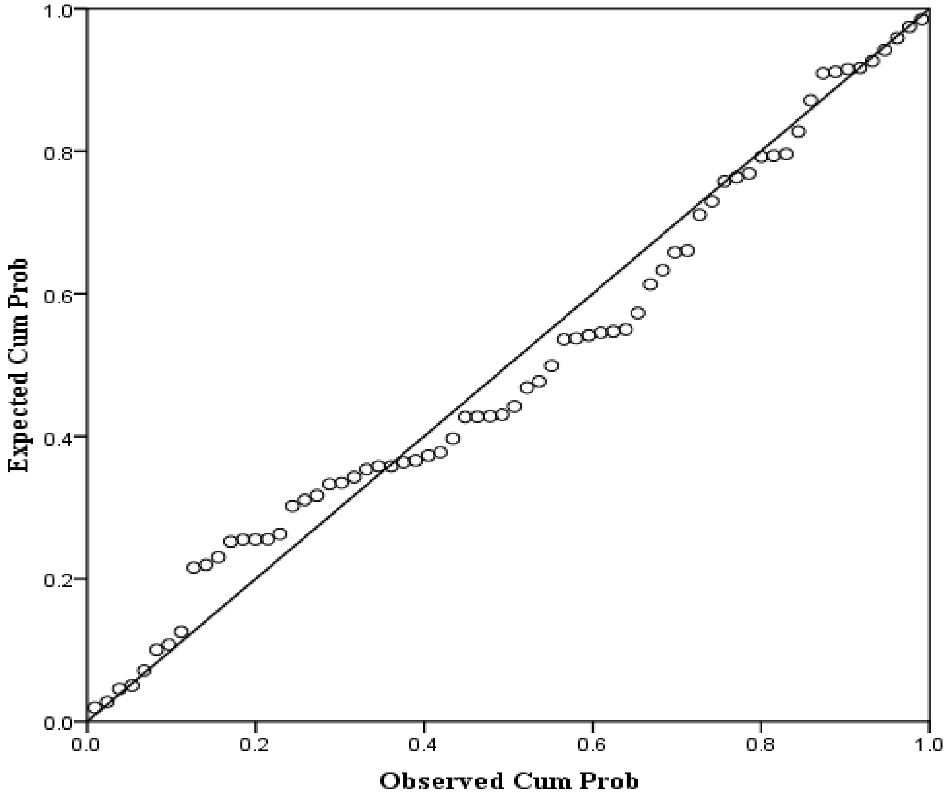


Fig. 6.22 Normal P – P Plot of Regression Standardized Residual Dependent Variable: Output% Permeability Decrease

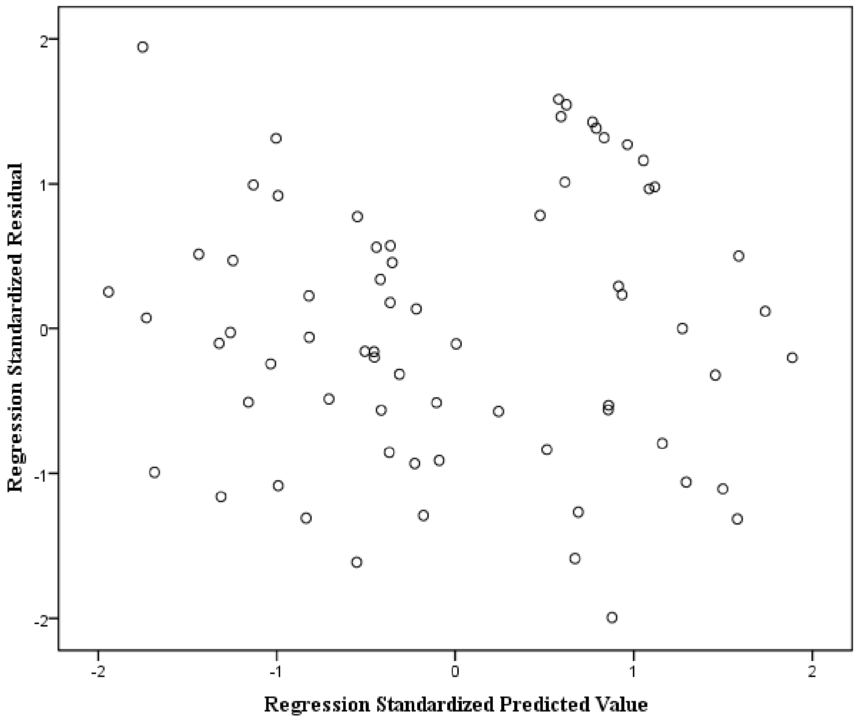


Fig. 6.23 Scatterplot Dependent Variable: Output % UCS Increase

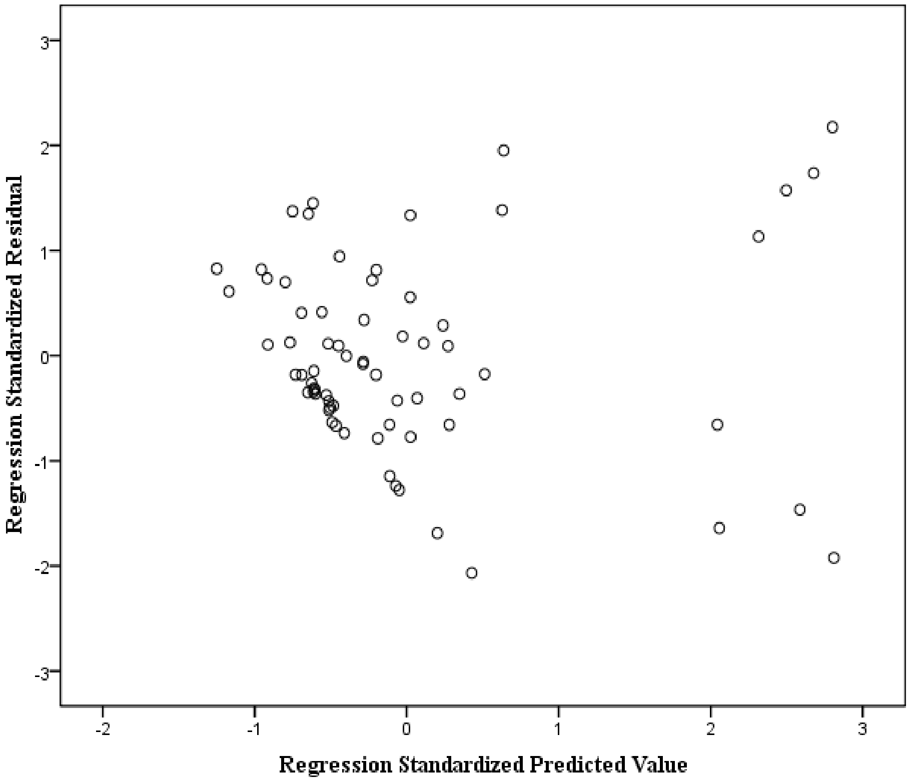
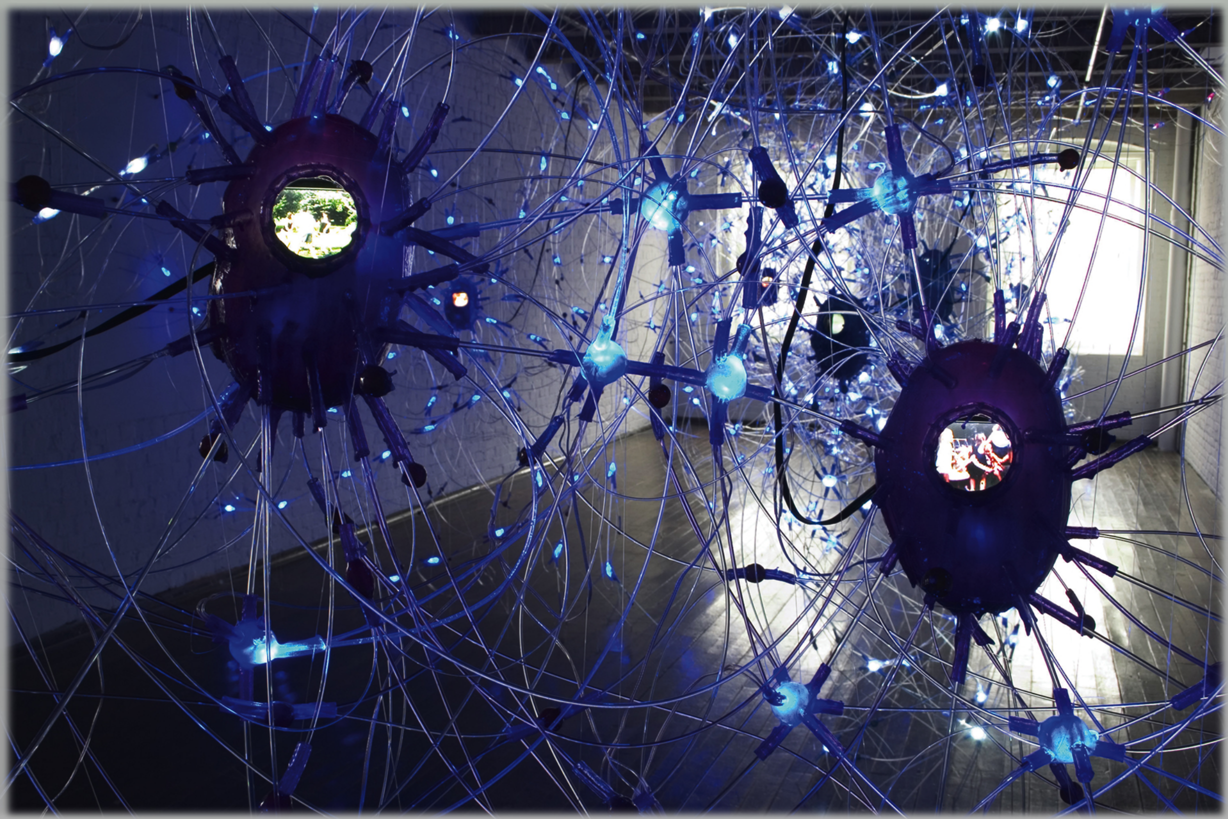


Fig. 6.24 Scatterplot Dependent Variable: Output% Permeability Decrease

The distribution of these plots should not be aligned to any corner or any side of the plot with the points being randomly placed amongst the plot area. This shows distribution of the predicted and the residual values which in turn goes to prove the non reliance of the model on any one particular variable used in the model.

CHAPTER 7

Artificial Neural Network for Electrokinetic Remediation



Artificial Neural Network for Electrokinetic Remediation of Nickel Contaminated Soil

Chapter Seven

In the recent years, many models and simulations have been tried to give a clear view about the various engineering problems which cannot be otherwise defined or modelled using conventional mathematical modelling techniques. Neural networks are adaptive statistical models based on an analogy with the structure of the brain. They are adaptive because they can learn to estimate the parameters of some population using a small number of exemplars (one or a few) at a time. Neural networks are used as statistical tools in a variety of fields, including psychology, statistics, engineering, econometrics, and even physics. They are used also as models of cognitive processes by neuro- and cognitive scientists. The true power and advantage of neural networks lies in their ability to represent both linear and nonlinear relationships as well as having the capability of learning by example. In comparison to traditional computing methods, neural networks offer a different way to analyze data and to recognize patterns within that data by being generic non-linear approximators.

When mathematical models fail to capture the input/output relationship within the limits of permissible error and sufficient data regarding the system available, artificial neural network is a pertinent tool to model successfully the system behaviour. ANNs are called model free models since they don’t rely upon a pre-defined mathematical equation to relate system input/output. A proper ANN structure is developed for each system to capture the system behaviour of a complex system. ANNs have been used for two main tasks: 1) function approximation and 2) classification problems. The application of neural networks to predict percentage of nickel removal from soil using electrokinetic removal belongs to the class of function approximation applications.

7.1 WHY USE NEURAL NETWORKS?

Neural networks, with their remarkable ability to derive meaning from complicated or imprecise data, can be used to extract patterns and detect trends that are too complex to be noticed by either humans or other computer techniques. A trained neural network can be thought of as an "expert" in the category of information it has been given to analyse. This expert can then be used to provide projections given new situations of interest and answer "what if" questions. Other advantages include:

- Adaptive learning: An ability to learn how to do tasks based on the data given for training or initial experience.
- Self-Organisation: An ANN can create its own organisation or representation of the information it receives during learning time.

- Real Time Operation: ANN computations may be carried out in parallel, and special hardware devices are being designed and manufactured which take advantage of this capability.
- Fault Tolerance via Redundant Information Coding: Partial destruction of a network leads to the corresponding degradation of performance. However, some network capabilities may be retained even with major network damage.

7.1.1 Historical Background

Neural network simulations appear to be a recent development. However, this field was established before the advent of computers, and has survived at least one major setback and several eras. Many important advances have been boosted by the use of inexpensive computer emulations. Following an initial period of enthusiasm, the field survived a period of frustration and disrepute. During this period when funding and professional support was minimal, important advances were made by relatively few researchers. These pioneers were able to develop convincing technology which surpassed the limitations identified by Minsky and Papert. Minsky and Papert, published a book in 1969 in which they summed up a general feeling of frustration (against neural networks) among researchers, and was thus accepted by most without further analysis. Currently, the neural network field enjoys a resurgence of interest and a corresponding increase in funding. The first artificial neuron was produced in 1943 by the neurophysiologist Warren McCulloch and the logician Walter Pits. But the technology available at that time did not allow them to do too much.

7.1.2 The Biological Prototype

Artificial Neural Networks (ANN) have emerged from studies of how the human brain performs various operations. The structure and functioning of human brain has been studied by many medical researchers. Even now the exact functional process of a human brain is not known. Basically, the brain functions with very dense network of neurons. The brain contains billions of neurons connected to each other by numerous connections amongst them. Figure 7.1 shows a typical biological neuron. The biological neuron consists mainly of the following parts:

- The cell body
- The axon
- The dentrite
- The synapse

The dentrite is responsible for carrying the signals from various other neurons to the neuron which it is a part of. These dentrites are spread in a branched form and carry signals in a very complex manner in the form of complicated electro-chemical signals. The axon carries the signals from the cell body to various other neurons. The dentrite and axon meet at a point which is called the synapse. Although it is often described as a meeting point, there is no physical contact between the axon and the dentrite at the synapse. The dentrites collect the signals at the synapse and then carry it to the cell body for further action. The dentrites do not get the signals at the synapses only. They may also get it directly from other cell body or even from the axon itself. When all dentrites carry the signals to the cell body, it is averaged up there. Here, after a comparison, if the average is more than the threshold value, then a signal is generated by the cell body and the same is sent down the axon. As billions of neurons work simultaneously in an extremely complicated network, the human brain can store a large amount of data and can recall it very quickly. As this complete process is not known clearly, it is not possible to develop an artificial neuron which is exactly similar to the biological neuron. Hence, an artificial neuron is developed as a very approximate model which can execute a simple mathematical function.

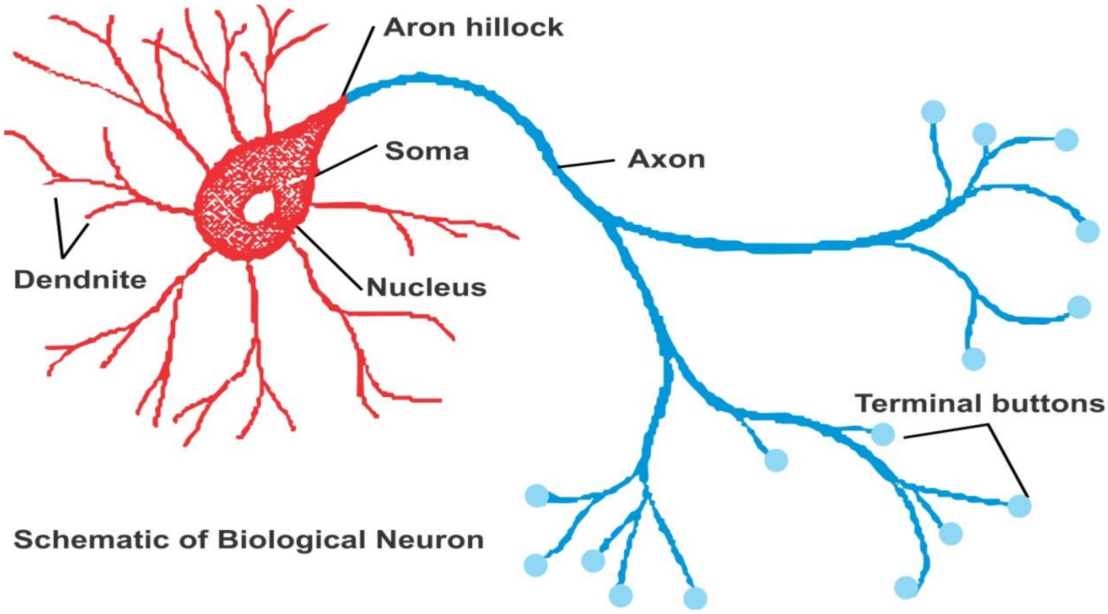


Fig. 7.1. A Biological Neuron

7.2 ARTIFICIAL NEURAL NETWORKS

An ANN has layers which are subgroups of processing elements. A layer of processing elements makes independent computations on data that it receives and passes the results to another layer. The next layer may in turn make its independent computations and pass on the results to yet another layer. Finally, a subgroup of one or more processing elements determines the output from the network. Each processing element makes its computation based upon a weighted sum of its inputs. The first layer is the input layer and the last layer is the output layer. The layers that are placed between the first and the last layers are the hidden layers. The processing elements are seen as units that are similar to the neurons in a human brain, and hence they are referred to as cells, neuromines or artificial neurons. Figure 7.2 describes an artificial neuron.

An artificial neuron has a typical function associated to it which is either called as threshold function or squashing function. The input and the output of the neuron are in an analog form and all computations are carried out using these analog signals only. A typical artificial neuron gets an input from other neurons or directly from the input nodes. The paths connecting the input nodes to the neurons and the connections between the various neurons are associated with a certain variable weight. These weights represent a multiplying factor for the incoming signal representing the synaptic strength of the connection. These weights are initially set to some random values and are later adjusted in the process of training the net. The artificial neuron then sums the input which is actually a weighted sum of all the input signals. The input so obtained is used to calculate a node value according to the squashing function of the neuron. This node value is compared with the threshold value of the neuron and if the node value is higher, then the neuron goes to the "excitation state" and a signal is passed on to the next layer of neurons. Figure 6.3 shows a layered feed-forward neural network. The circular nodes represent neurons. Here there are four layers, an input layer, two hidden layers, and an output layer.

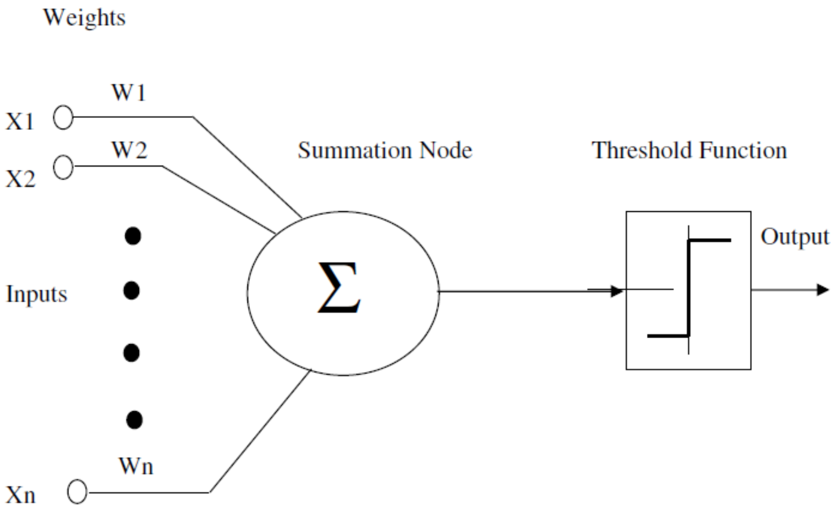


Fig. 7.2. An Artificial Neuron

7.2.1 Neural Network Classification

The term neural network is referenced in many areas & therefore, distinction between various types of neural networks is necessary. There are three important types of neural networks. (Fig. 7.3, 7.4 & 7.5). A biological neural network is found in living organisms such as human brain whereas an Artificial Neural Network (ANN) uses electronic circuits to model biological neurons & their interactions. ANNs use many simple interconnected electronic processing elements to simulate the interconnected neurons of brain. When computer algorithms are developed to model biological neurons, these are referred to as Simulated Artificial Neural Networks (SANN) as a branch of science. ANN are very expensive to implement, SANN could be implemented with great deal of flexibility. Thus, SANN is an attempt to mimic the action of brain by using similar structure. It consists of artificial neurons consisting a class of adaptive machines that perform computations through process of learning. The ANN and SANN can be classified as follows based upon following important characteristics:

1. Network topology or architecture and
2. Learning method

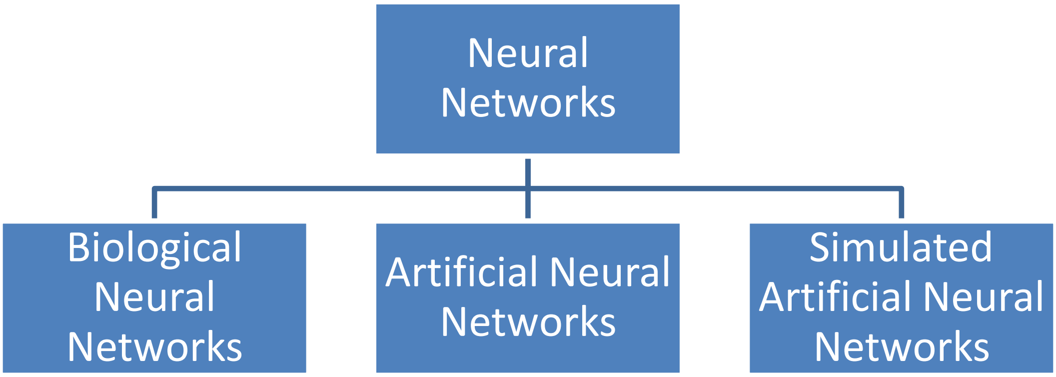


Fig.7.3 Types of Neural Networks

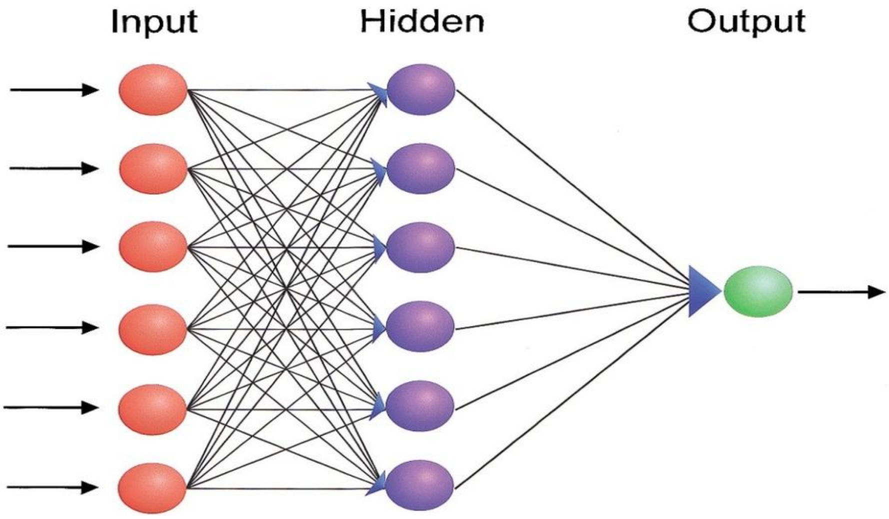


Fig. 7.4. Typical Feed Forward Neural Network

Feed Forward neural networks are the ones where the data from input to output units is strictly feed forward. The data processing can extend over multiple (layers of) units, but no feedback connections are present, that is, connections extending from outputs of units to inputs of units in the same layer or previous layers are not permitted. The neural structures in brain are largely feed forward layered networks. Rosenblatt [1957] gave the concept of perceptron as layered feed forward network. There may be one or more intermediate layers, followed by output layer. The output of a layer is not fed to the same layer or preceding layers. Thus, signals flow in forward direction only. 'Adaptive linear element,' also named Adaline, developed by Widrow and Hoff [1960] is another example of feed forward networks.

7.2.2 Architecture Elements

The major constructional elements of a neural network model are described in this section.

7.2.2.1 Cell

A cell (or unit) is an autonomous processing element that models a neuron. Cell can be thought of as a very simple computer. The purpose of cell is to receive information from other cells, perform relatively simple processing of the combined information and send the results to other cells. In illustrations of neural networks, cells are usually indicated by circles or squares. Cells in a network are denoted and numbered as u_1, u_2, u_3, u_4, …..

7.2.2.2 Layers

A layer is a collection of cells that can be thought of as performing some type of common function. These cells are usually ordered by placing numbers or letters by each cell. It is generally assumed that cells in same layers do not connect to communicate. All neural nets have an input layer & an output layer to interface external world / environment. Each input layer & each output layer has at least one cell in respective layer. The simplest type of neural net has only one input layer & one output layer. The members of this first class of neural networks have been called two layer networks & one layer networks (one-layer since only output layer has weights). Such a network is indicated in Figure 7.6. A cell that is not in input layer or output layer is said to be in hidden layer since, the input or output of cells in this layer are not observable from outside. Sometimes the cells in hidden layer are called feature detectors because they respond to particular features in previous layer. A neural network with two hidden layer is shown in Figure 7.7.

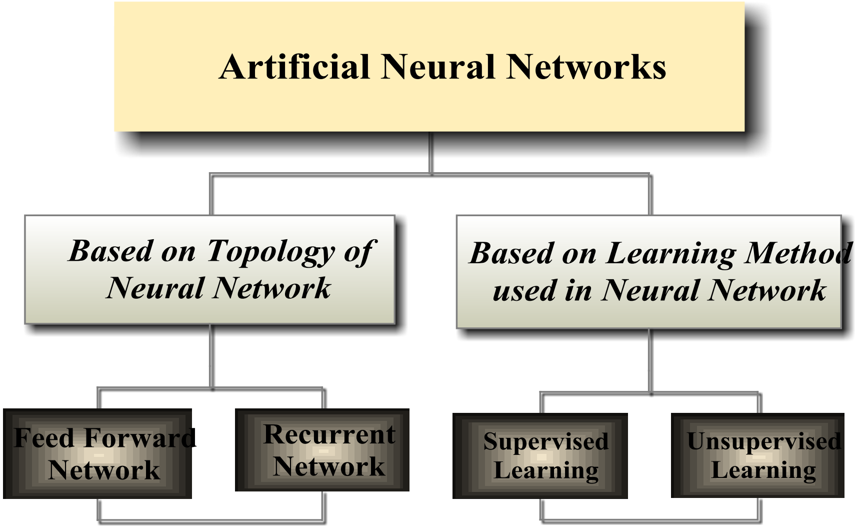


Fig. 7.5 Classifications of Artificial Neural Networks and Simulated Neural Networks

7.2.2.3 Arcs

An arc (or connection) can be one way or two way communication link between cells. A feed-forward network is one in which the information flows from the input cells through any hidden layers to the output cells without any paths whereby a cell in a lower numbered layer receives input from a cell in a higher numbered layer. A feedback network by contrast also permits communication backwards.

7.2.2.4 Weights

A weight w_{ij} is a real number that indicates the influence that cell u_j has on cell u_i. For example, positive weights indicate reinforcement; negative weights indicate inhibition & zero weight indicate absence of direct influence or existence of connection. Weights are often combined into a matrix W. These weights may be initialized as zero, initialized as given & predefined values or initialized as random numbers, but they can be altered by experience. It is in this way that the system learns. Weights may be used to modify the input from cells. However, the cells in the input layer have no weights; that is, the external inputs are not modified before going into the input layer.

7.2.3 Output of a Neuron

Basically, the internal activation or raw output of a neuron in a neural network is weighted sum of its inputs, but a threshold function is used to determine the final value, or the output. When the output is 1, the neuron is said to fire, and when it is 0, the neuron is considered not to have fired. When a threshold function is used, different results of activations, all in the same interval of values, can cause the same output value. This situation helps in the sense that, if precise input causes an activation of 9 and noisy input causes an activation of 10, then the output works out the same as if noise is filtered out.

7.2.4 Network Training

Since the outputs may not be what is expected, the weights may need to be altered. Some rule then needs to be used to determine how to alter the weights. There should also be a criterion to specify when the process of successive modification of weights ceases. This process of changing the weights, or rather updating the weights, is called TRAINING. A network in which learning is employed is said to be subjected to training.

7.2.5 Information Feedback

If you wish to train a network so it can recognize or identify some predetermined pattern, or evaluate some function values for given arguments, it would be important to have information feedback from the output neurons to the neurons in some layers before that, to enable further processing and adjustment of weights on the connections. Such feedback can be to the input layer or a layer between the input layer and the output layer, sometimes labelled the hidden layer. What is feedback is usually the error in the output, modified appropriately according to some useful paradigm. The process of feedback continues through the subsequent cycles of operation of the neural network and ceases when the training is completed.

7.2.6 The Threshold Function

The output of any neuron is the result of thresholding, if any, of its internal activation, which in turn, is the weighted sum of the neuron inputs. Thresholding (scaling) is important for multilayer networks to preserve a meaningful range across each layers operation. The most often used threshold function is the SIGMOID function. A STEP function or a RAMP function or just a LINEAR function can be used. The range of activation function (i.e. the value it can output) is usually limited. The most common limits are 0.0 to 1.0 and -1.0 to 1.0. If the weighted sum of the inputs is less than the threshold, the output of the neuron is 0, otherwise the output is 1. This type of function is called as STEP function because of its shape resembles like a step as shown in Figure 7.8.

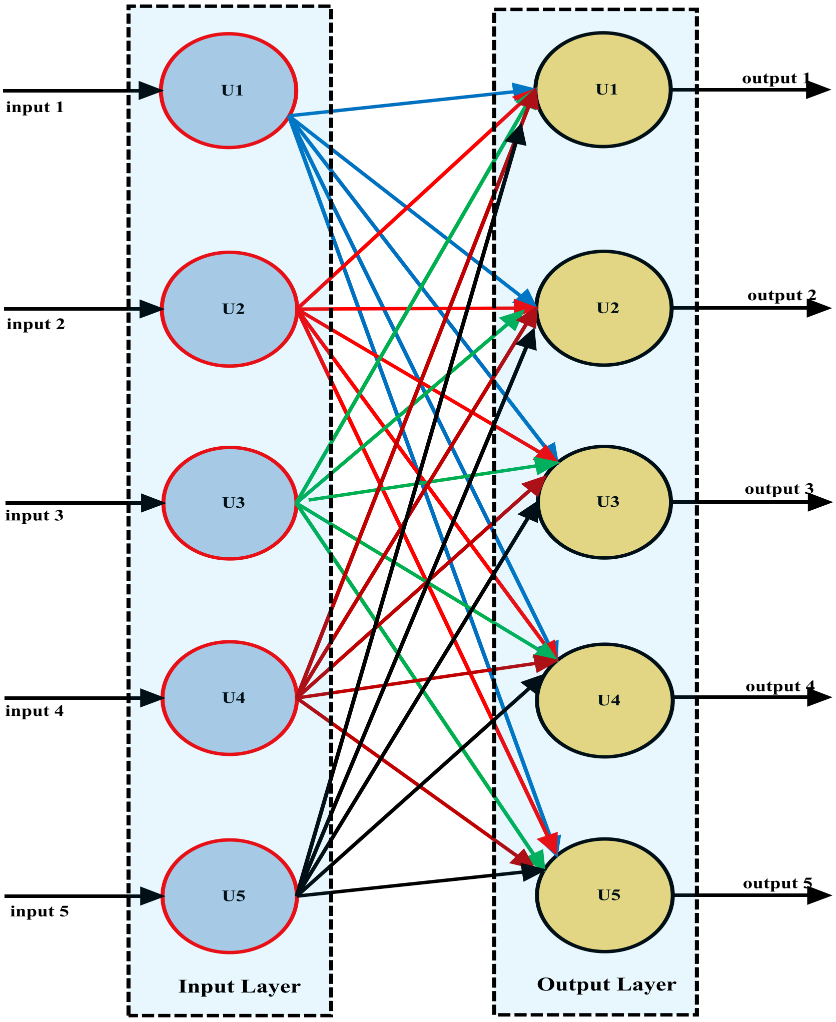


Fig. 7.6 Artificial Neural Network with Input & Output Layers
(No Hidden Layers)

The other type of threshold function is the SIGMOIDAL function and is a nonlinear function, Figure 7.9. Mathematically this sigmoidal function or logistic function is expressed as

$$f(x) = \frac{1}{1 + e^{-x}}$$

Most neural network applications have been successfully applied using this sigmoidal function because of its derivative is simple and always positive. Another commonly used threshold function is the HYPERBOLIC TANGENT, Figure 7.10. Mathematically, it is expressed as

$$\tan h(x) = \frac{e^{x} - e^{-x}}{e^{x} + e^{-x}}$$

It is similar to the shape of the logistic or sigmoidal function, but is symmetrical about the origin. Unlike the sigmoidal function, the hyperbolic tangent function has a bipolar value for output, a characteristic that has been shown to be beneficial to certain network applications.

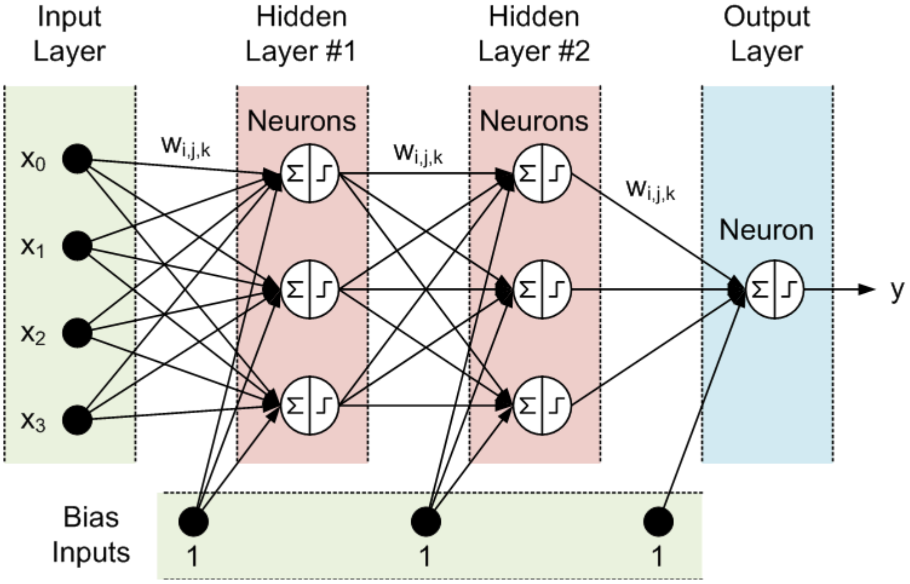


Fig. 7.7 Neural Network with Hidden Layer

7.2.7 Back Propagation Model

The feed forward back propagation network is a very popular model in Neural Networks. It does not have feedback connections, but errors are back propagated during training. The feed forward back propagation network undergoes supervised training, with a finite number of pattern pairs consisting of an input pattern and a desired or target output pattern. An input pattern is presented at the input layer. The neurons here pass the pattern activations to next layer neurons, which are in a hidden layer. The outputs of the hidden layer neurons are obtained by using bias, and also a threshold function with activations determined by the weights and the inputs. These hidden layer outputs become inputs to the output layer, which process the inputs using bias values and threshold function. The final output of the network is determined by the activations from the output layer. The process of developing back prorogation algorithm often involves experimentation. It is difficult to determine how many hidden layer neurons are to be provided for. In general, the size of the hidden layers is related to the features that should be discerned from the data. In this work, a double hidden layer network is used with sigmoidal function as the threshold function and varying bias values for all the neurons.

7.2.8 Configuration of Network

The complete network development process of the back propagation network consists of

- Selection of the network parameters such as the number and size of different layers of the network, nodal function, etc.
- Selection of input and output pattern.
- Selection of learning rule and other learning parameters to enhance the learning capability and speed.

- Initialization of the network and learning till the network learns the desired relationship between the input and the output vectors.

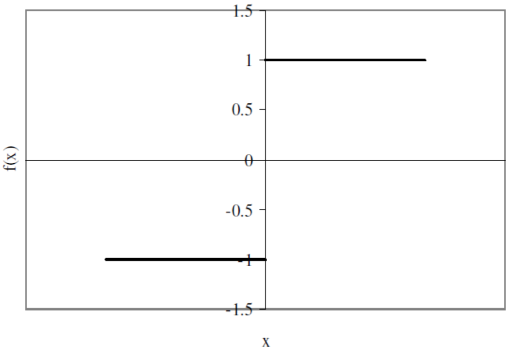


Fig. 7.8. Hard Limiter or Step Function

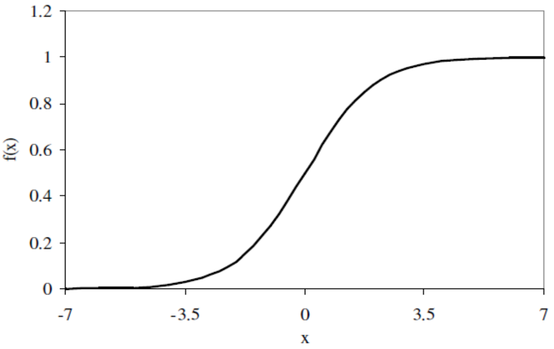


Fig. 7.9 The Sigmoidal Function

The network configuration stage consists of

- **Selecting input vector:** The input layer for all the networks are configured taking into account the possible parameters which may influence the output. As the network is supposed to learn the unknown functional relationship between the input and the output parameters, the performance of the network is highly sensitive to the input information. Usually, numbers of input nodes are equal to the input parameters. Sometimes, an extra input node is considered for training purpose which serves as a bias node. The weight values associated with this node are bias values which change along with the network weights. Using bias node helps the network to learn the relationship fast. In this research, bias nodes are used for the input and hidden layers.

- **Selection of output vector:** The selection of output layer nodes is apparently the most simple task in the development of any network. The numbers of output nodes are often automatically decided by the number of desired output parameters.

- **Selection of threshold function:** The selection of threshold function for the neurons is most important because it affects the learning speed of the network. It depends mainly on the intended use of the network and method of learning.

Since the back propagation learning algorithm has been used to train feed forward network in this work, the sigmoidal nonlinear nodal function has been used.With the help of hard limiter function, the weights of the different connection links cannot be made to learn. This is because, according to the learning rule for perceptron, only the active connections are strengthened. To overcome this disadvantage, a function which is continuous and which closely follows the hard limiter is to be used. The sigmoidal function is a continuous one. Moreover, it goes from low to high for very small variation in input.

The sigmoidal non linearity has been used in the present work because of the following reasons:

- It represents the response of the actual neuron very closely.
- It has a very simple derivative which is useful in the development of the training algorithm.

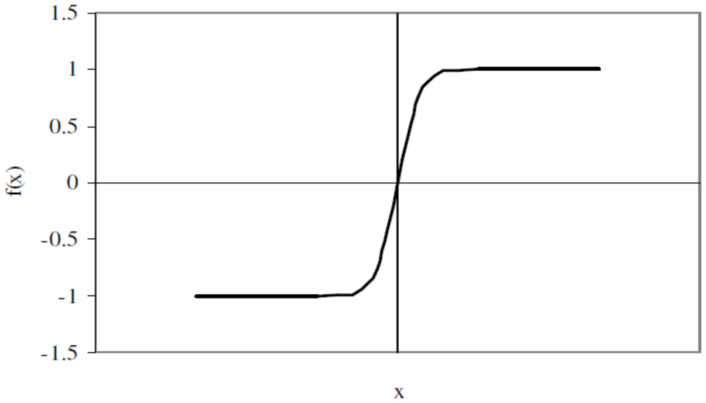


Fig. 7.10 The Hyperbolic Tangent

The sigmoidal function is given by

$$f(x) = \frac{1}{1 + e^{-x}}$$

The derivative of this function is

$$f^{'}(x) = \frac{e^{-x}}{(1 + e^{-x})^2} = \frac{f(x)}{1 - f(x)} = Y(1 - Y)$$

This simple derivative facilitates quick calculations in the learning algorithm for the back propagating algorithm. The sigmoidal nodal function acts as automatic gain controller. The gain term for weight correction, which is proportional to the slope of the nodal function in back propagation, is automatically controlled.

- **Configuration of hidden layers:** The selection of the number of hidden layers and the number of nodes in the hidden layers is the most challenging part in the total network development process. Unfortunately, there are no fixed guidelines available for this purpose and hence, it is required to be done by trial and error method. Although some investigators have tried to arrive at an approximate formula, still there is no reliable method available. It is proved that with sufficient number of nodes, any functional relationship can be mapped using a network having single hidden layer. However, increase in number of hidden layers possibly improves the generalization capacity.

- **Presenting training pairs:** The training set is presented to the network till it learns the internal representation of a physical phenomenon from training pairs. Normally, it takes a long time for a successful training of networks using back propagation algorithm. In addition, to start with, the initial weights and the bias values are randomly chosen. This has a large impact on the training time. For a particular set of weights and bias values, the net may get paralysed i.e. it may stop learning altogether. This is caused due to the weights and bias values getting adjusted to a disproportionately large value. In such a case, learning process has to be restarted with a new set of weights and biases.

7.2.9 Steps of Back Propagation

The back propagation incorporates a learning algorithm called the "Generalized Delta Rule" which is responsible for training of the net. The task in training is to determine a unique set of network weights that enables the network to map the desired output sets. Once the mapping is achieved, the network is said to be knowledgeable about all the training pairs. The training procedure can be summarized in the following steps:

- Let A be the number of neurons in the input layer, as determined by the length of the training input vectors. Let D be the number of neurons in the output layer. Now choose B and C, the number of neurons in the hidden layers. As shown in Figure 7.11, the input and hidden layers have an extra unit used for thresholding; therefore, the units in input and hidden layers are indexed by the ranges (0, ..., A), (0,....,B) and (0,...,C).
- Initialize all the weights of the network with random values between -0.1 and +0.1.

$w1_{ij}$ = random(−0.1, 0.1) for all i = 0, ...A, j = 1, ...B
$w2_{ij}$ = random(−0.1, 0.1) for all i = 0, ...B, j = 1, ...C
$w3_{ij}$ = random(−0.1, 0.1) for all i = 0, ...C, j = 1, ...D

- Initialize the activations of the bias units. The values of these bias units should never change. The weights associated with these units act as the bias values for each neuron and change along with other weights for the network. $x_0 = 1.0$ $h1_0 = 1.0$ $h2_0 = 1.0$
- Present input - output pair. Suppose the input vector is x_i and the target output vector is y_i.
- Propogate the activations from the units in the input layer to the units in the first hidden layer using the Equation given below

$$\mathrm{h1}_j = \frac{1}{1 + e^{-\sum_{i=0}^{A} x_i \mathrm{w1}_{ij}}} \text{ for all j =1,.......B}$$

- Propogate the activations from the units in first hidden layer to the units in the second hidden layer.

$$\mathrm{h2}_j = \frac{1}{1 + e^{-\sum_{i=0}^{B} \mathrm{h1}_i \mathrm{w2}_{ij}}} \text{ for all j =1,.......C}$$

- Propogate the activations from the units in second hidden layer to the units in the output layer.

$$\mathrm{o}_j = \frac{1}{1 + e^{-\sum_{i=0}^{C} \mathrm{h1}_i \mathrm{w3}_{ij}}} \text{ for all j =1,.......D}$$

- Compute the errors of the units in the output layer, denoted by δ3j.

$$\delta 3_j = o_j(1 - o_j)(y_j - o_j) \text{ for all j} = 1,\ldots\ldots.\text{D}$$

- Compute the errors of the units in both the hidden layers, denoted by δ2j , and δlj, respectively.

$$\delta 2_j = \text{h}2_j(1 - \text{h}2_j)\sum_{i=1}^{D} \delta 3_i\, w3_{ji} \text{ for all j} =1,\ldots\ldots\ldots,\text{C}$$

$$\delta 1_j = \text{h}1_j(1 - \text{h}1_j)\sum_{i=1}^{C} \delta 2_i\, w2_{ji} \text{ for all j} =1,\ldots\ldots\ldots,\text{B}$$

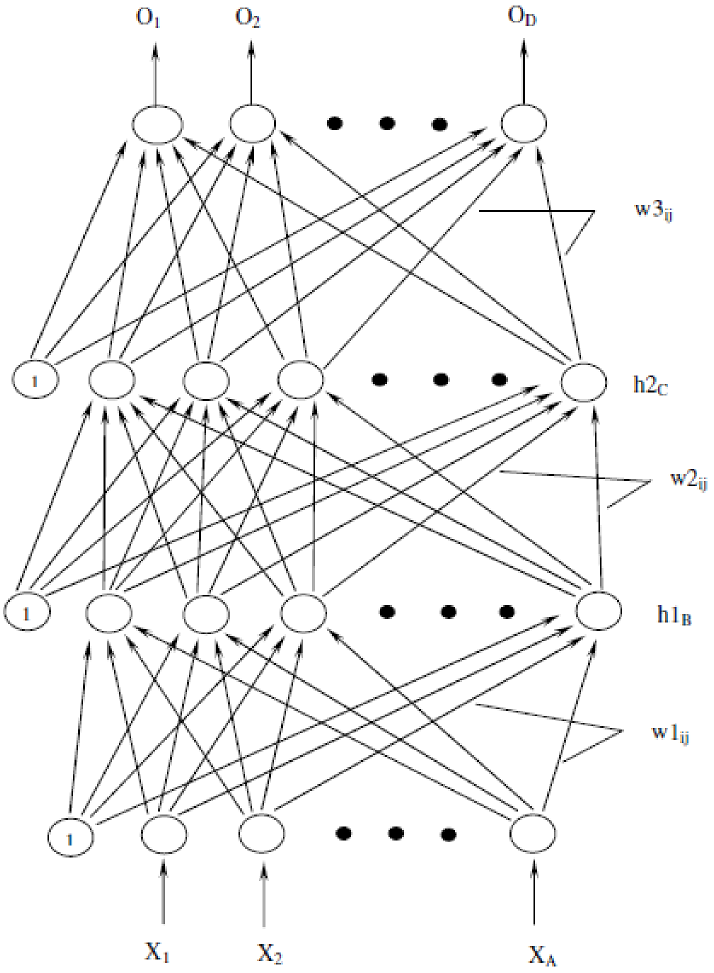


Fig. 7.11 Back Propagation Neural Network

- Modify the weights between all the layers as per the following equations. The learning rate is denoted by η and the momentum rate is denoted by α. Both values are less than unity.

$$\Delta \text{w}3_{ij}(t+1) = \eta\delta 3_j \text{h}2_i + \alpha\Delta w3_{ij}(t) \text{ for all i} = 0,\ldots.,\text{C, j} = 1,\ldots.,\text{D}$$

$$\Delta \text{w}2_{ij}(t+1) = \eta\delta 2_j \text{h}1_i + \alpha\Delta w2_{ij}(t) \text{ for all i} = 0,\ldots.,\text{B, j} = 1,\ldots.,\text{C}$$

$$\Delta \text{w}1_{ij}(t+1) = \eta\delta 1_j \text{x}_i + \alpha\Delta w1_{ij}(t) \text{ for all i} = 0,\ldots.,\text{A, j} = 1,\ldots.,\text{B}$$

where (t + 1) denotes the current cycle or epoch.

- Go to step 4 and repeat. When all the input - output pairs are presented to the network, one epoch is complete. Steps 4 to 10 are repeated till the network output converges.

7.2.10 Enhancing the Simulator

The back propagation networks are capable of providing accurate approximations to any function that links the training pairs, provided a proper network topology is used. Despite its capabilities, back propagation algorithm suffers from some drawbacks that makes the development of ANN model a difficult task that is neither straight forward, nor simple. The important drawbacks of back propagation algorithm are summarized as follows.

- **Network Paralysis:** The network paralysis is caused by weights having very large values. During the training, if weights get adjusted to very large values, the neurons operate at very large values i.e. in the region of the sigmoidal function where its derivative is very small. As the weight changes are proportional to the derivative, the weight changes affected by the back propagation algorithm are negligible. Therefore, the network virtually stops learning.

- **Local Minima:** This is caused when the weight vector gets trapped in local minima. Since the back propagation algorithm uses steepest descent method, it takes the weight vector downward on the error surface by adjusting the weights. If the error surface is full of hills and valleys, the weight vector may get trapped in local a minimum that is nearest to the starting point. There are many variations of the algorithm that try to alleviate the above two drawbacks of back propagation. You may need to shake the weights a little by some means to get out of local minima, and possibly arrive at lower minima. For the paralysis which may attack the network weights, only solution is to initiate with new sets of weights. The following actions do help to overcome these difficulties to some extent.

- **Adding the momentum term:** A simple change to the training law that sometimes results in much faster training is the addition of a momentum term of momentum factor. This term enables the network to overcome the local minima problem to some extent. Also, it helps in preventing the oscillations of the weight vector. The weight change expression according to back propagation algorithm, as expressed by equations (6.11), (6.12) and (6.13) is

$$\Delta \mathrm{w}_{ij}(t+1) = \eta \delta 3_j \mathrm{h2}_i + \alpha \Delta w_{ij}(t)$$

  The second term in the above equation is known as momentum term. $\alpha\Delta wij(t)$ is the error or previous weight change. The value of α is less than 1. The use momentum term keeps the weight change process moving, and thereby not allowing the weight values to get stuck into local minima.

- **Adding bias during training:** Another approach to breaking out of local minima as well as to enhance generalization ability is to introduce some BIAS in the inputs during training. A random number is added to each neuron of the hidden layers and output layer in the feed forward direction. These bias values change according to same weight change law after every epoch.

The other possible methods to overcome the limitations of back propagation algorithm are adjusting the learning rate parameter, η, revising the network configurations, etc. There are no particular laws to change or modify the above factors, however it is totally dependent on the individual to compare these values during training and change correspondingly.

7.2.11 Selection of Modelling Tools

There are many ways to implement artificial neural networks. It is difficult to find optimal network architecture, considering the uniqueness of each system or problem. Usually, a prior choice, such as selection of network topology, training algorithm and network size should be made based on experience in order to keep the task to a manageable proportion. Further, for modeling of systems an appropriate modeling platform is essential. Artificial neural network models for any system can be developed using one of the following three tools.

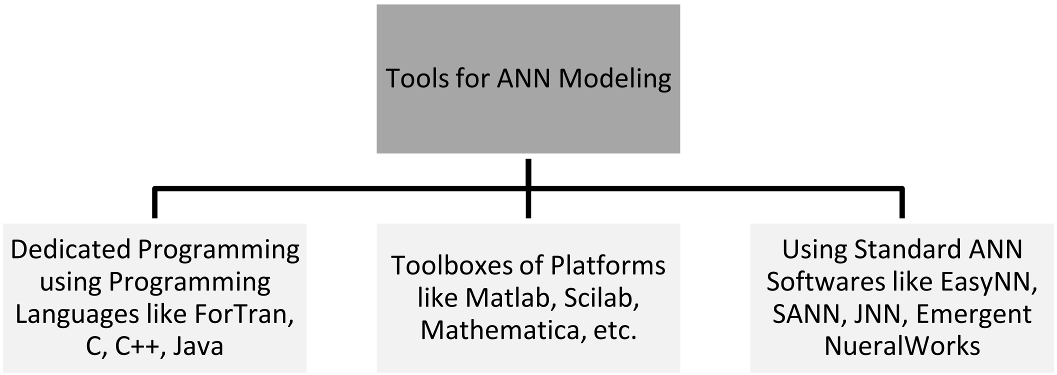


Fig. 7.12 Tools for ANN Modeling

As given in Figure 7.12, there are numerous neural network simulation softwares available which allow fast development of neural networks. These softwares provide menus and graphics to define the network in terms of layers and cells in each layers, the propagation rule, activation rule, output function and learning algorithm. They allow feeding of input/output matched pairs termed as patterns for learning and validation. The permissible error for the validation set can also be specified. The weights and bias are updated and the network is tuned. The learning terminates either on the basis of number of cycles permitted for learning and validation or on achievement of error values less than the target values specified.

Such simulation softwares can be further divided into executables and open source softwares. The executables like EasyNN, NeuralWorks etc. come with binary code and provide predefined functionality. This predefined functionality cannot be altered or extended by programming. The behaviour of the software in terms of definition of various network elements is predefined and cannot be modified if this behaviour is not satisfactory for a particular system. Further, the set of functions defined is also fixed. If neither of the functions in this set is suitable for the modelling of a particular system, the software is rendered in appropriate for modelling of that system. On the other hand, the open source softwares, in addition to providing some predefined functionalities, come with the source code and permit the modification and extension of the software definition. SANN, Genesis etc. are examples of such neural network simulation softwares with open source.

If these softwares do not satisfy the problem requirement, the next choice is to use the neural network modelling toolboxes available with programming platforms like MATLAB and Scilab. These toolboxes provide fast development platform since ready to use ANN specific functions are made available as library functions. Graphical functions of these platforms permit faster development. If these ready libraries do not satisfy certain peculiar system, the most flexible yet most time consuming option is to develop a dedicated program using any of the programming language syntax. All the graphics and other functionalities have to be defined in this case.

7.3 SELECTED ARCHITECTURE AND INPUT - OUTPUT PARAMETERS

The present analysis has been carried out using EasyNN software using different number of hidden layers each consisting of varying number of neurons. The details of input and output variables and the selected architecture for analysis are given in Table 7.1 and 7.2. The total numbers of data sets available have been divided into two sets, one for training and the other for verification.

7.3.1 Error Calculations

Error for each case is defined as mentioned below

$$Error\ (\%) = \frac{|A_e - A_p|}{A_e} \qquad (7.1)$$

where, A_e = the output value as obtained from theoretical analysis, A_p = the output value predicted by the neural network model. The average error for entire epoch (complete set of input-output pairs) is defined as

$$Error_{av}(\%) = \frac{1}{N}\sum_{i=1}^{N}\frac{|A_{ei} - A_{pi}|}{A_{ei}} \qquad (7.2)$$

Table 7.1 List of Parameter with Scaling Factors

Output and Input Parameters	Denotation	Scaling Factor
Percentage of removal (Output)	OR	= OR/100
Initial Concentration (Input_1)	X	= X/1000*1.5
Anode Solution (Input_2)	AS	As per Table 6.4
Conc. Of Anode (Input_3)	Y	= SQRT(Y)
Cathode Solution (Input_4)	CS	As per Table 6.4
Conc. Of Cathode (Input_5)	Z	= SQRT(Z)
Voltage Applied (Input_6)	V	= V/100*2
Current (Input_7)	C	= (SQRT((LOG(C))*-0.1))*1.25
Current Density (Input_8)	CD	= (SQRT((LOG(CD))*-0.1))*1.25
Ambient Temperature (Input_9)	AT	= AT*2/100
Temp. Anode (Input_10)	TA	= TA/100*1.5
Temp. Center (Input_11)	TCe	= TCe/100*1.5
Temp. Cathode (Input_12)	TC	= TC/100*1.5
Voltage Anode (Input_13)	VA	= (SQRT(VA/100))*1.5
Voltage Center (Input_14)	VCe	= SQRT(VCe/100))*1.5
Voltage Cathode (Input_15)	VC	= (SQRT(VC/100))*1.5
Length of Sample (Input_16)	L	= L/150
Cross Sectional Area (Input_17)	CS	= CS/100

The maximum error is defined as $Error_{\max}\% = \max\left(\sum_{i=1}^{N}\frac{A_{ei}-A_{pi}}{A_{ei}}\right)$ (7.3)

and the minimum error is defined as $Error_{\min}\% = \min\left(\sum_{i=1}^{N}\frac{A_{ei}-A_{pi}}{A_{ei}}\right)$ (7.4)

For each architecture of neural network model the root mean square value of error is

$$\mathrm{Error}_{\mathrm{rms}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{A^{e}-A^{p}}{A^{e}}\right)^{2}} \qquad (7.5)$$

For determination of the rms error, the maximum error out of the output node is used. The confidence R and scatter σ test can be used to decide upon the best architecture. The R and σ values can be determined as

$$R = \frac{1}{N}\sum_{i=1}^{N}R_{i} = \frac{1}{N}\sum_{i=1}^{N}\frac{A^{e}}{A^{p}} \qquad (7.6)$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\{R-R_{i})^{2}} \qquad (7.7)$$

The universal approximation theorem shows that a neural network with a single hidden layer with a sufficiently large number of neurons can in principle relate any given set of inputs to a set of outputs to an arbitrary degree of accuracy. The determination of the number of neurons in the hidden layer is more art than science. A trial and error method is therefore adopted in the study (Table 7.2) to optimize the number of neurons in the hidden layer. Also since that output for the given problem is a single output optimization for the number of neurons is carried out by also increase the number of hidden layers.

Table 7.2 Selected Architecture for Analysis

Total Number of Layers	Number of Hidden Layers	Nodes in 1^{st} Hidden Layer	Nodes in 2^{nd} Hidden Layer	Nodes in 3^{rd} Hidden Layer	Model Designation
Three	One	3			17,3,1
		4			17,4,1
		6			17,6,1
		8			17,8,1
		10			17,10,1
		12			17,12,1
Four	Two	3	3		17,3,3,1
		3	5		17,3,5,1
		3	7		17,3,7,1
		5	3		17,5,3,1
		5	7		17,5,7,1
		7	7		17,7,7,1
		9	9		17,9,9,1
Five	Three	3	3	3	17,3,3,3,1
		3	3	5	17,3,3,5,1
		5	3	3	17,5,3,3,1
		5	5	3	17,5,5,3,1
		3	5	3	17,3,5,3,1
		5	5	5	17,5,5,5,1
		7	7	7	17,7,7,7,1

7.3.2 Sensitivity Analysis

Mathematical models are utilized to approximate various highly complex engineering, physical, environmental, social, and economic phenomena. Model development consists of several logical steps, one of which is the determination of parameters which are most influential on model results. Applications of computational models to complex processes are often subject to uncertainty. In many cases this uncertainty is of "epistemic" type, i.e. it is due to the imprecise knowledge of deterministic parameter values, phenomena, model assumptions. The aim of sensitivity analysis in such cases is to quantitatively express the degree of impact of the uncertainty from the specific sources on the resulting uncertainty of final model output. This information helps the analyst to identify the most important contributors to output uncertainty, model validation and as a guide to future research efforts. Sensitivity analyses is conducted for a number of reasons including the need to determine:

- Identify parameters which require additional research for strengthening the knowledge base, thereby reducing output uncertainty;
- Identify insignificant parameters so as to eliminate those from the final model;
- Identify inputs contributing most to output variability;
- Identifying parameters which are most highly correlated with the output; and
- Identifying the consequence on result from changing a given input parameter, once the model is in production use.

There are many different ways of conducting sensitivity analyses; however, in answering these questions the various analyses may not produce identical results (Iman and Helton, 1988). Generally, sensitivity analyses are conducted by:

- Defining the model and its independent and dependent variables
- Assigning probability density functions to each input parameter,
- Generating an input matrix through an appropriate random sampling method,
- Calculating an output vector, and
- Assessing the influences and relative importance of each input/output relationship.

Many authors, when referring to the degree to which an input parameter affects the model output, use the terms 'sensitive', 'important', 'most influential', 'major contributor', 'effective', or 'correlated' interchangeably (Iman and Helton, 1988; Marguiles et al., 1991). The consensus among authors is that models are indeed sensitive to input parameters in two distinct ways:

- The variability, or uncertainty, associated with a sensitive input parameter is propagated through the model resulting in a large contribution to the overall output variability, and
- Model results can be highly correlated with an input parameter so that small changes in the input value result in significant changes in the output.

The necessary distinction between important and sensitive parameters is in the type of analysis being conducted: uncertainty analysis (parameter importance) or sensitivity analysis (parameter sensitivity). An important parameter is always sensitive because parameter variability will not appear in the output unless the model is sensitive to the input. A sensitive parameter, however, is not necessarily important because it may be known precisely, thereby having little variability to add to the output. At the completion of an analysis on parameter sensitivity the analyst holds a list, or 'sensitivity ranking', of the input parameters sorted by the amount of influence each has on the model output. The actual ranking is not as important as is the specification of which parameters consistently appear near the top of the list. Of the various methods of sensitivity analysis utilized for various modelling situations, the present work uses the sensitivity index method for Artificial Neural Networks.

7.3.3.1 The Sensitivity Index

Another of the simple methods of determining parameter sensitivity is to calculate the output % difference when varying one input parameter from its minimum value to its maximum value (Hoffman and Gardner, 1983; Bauer and Hamby, 1991). Hoffman and Gardner (1983) advocate utilizing each parameter's entire range of possible values in order to assess true parameter sensitivities. A sensitivity analysis was performed on the chosen ANN's so that a better understanding of the relative importance of each input on the output could be examined. Thus, sensitivity analysis was carried out to investigate the dynamic behaviour of input variables. This was done by imposing steps changes to various inputs and observing their effects on the network output. These responses were used as guides to select appropriate input variables that are suitable for model development.

When studying the sensitivity of the neural network models it is also necessary to define the solution in the form that achieves the best compromise between certain selected relevant and conflicting criteria. This criterion often calls on deciding the model architecture taking into consideration one variable at a time. All conventional statistical and computing techniques, using either linear or non linear relations have merit when modelling quantifiable parameter but most are incapable of handling qualitative facts that have significant impact on the electrokientic remediation prediction. There is ample proof that whenever using ANN, the use of sensitivity analysis along with it has an attractive advantage over the traditional statistical methods. This is true since first, ANN have no requirement of predetermining the relationships between inputs and outputs, second, they require no assumption regarding the data following a specific statistical distribution and third ANNs have a very strong capability of self learning and self updating. For this very reason a detailed sensitivity analysis is presented in the work along with study of various neural architectures.

7.3.3 Three Layer Networks

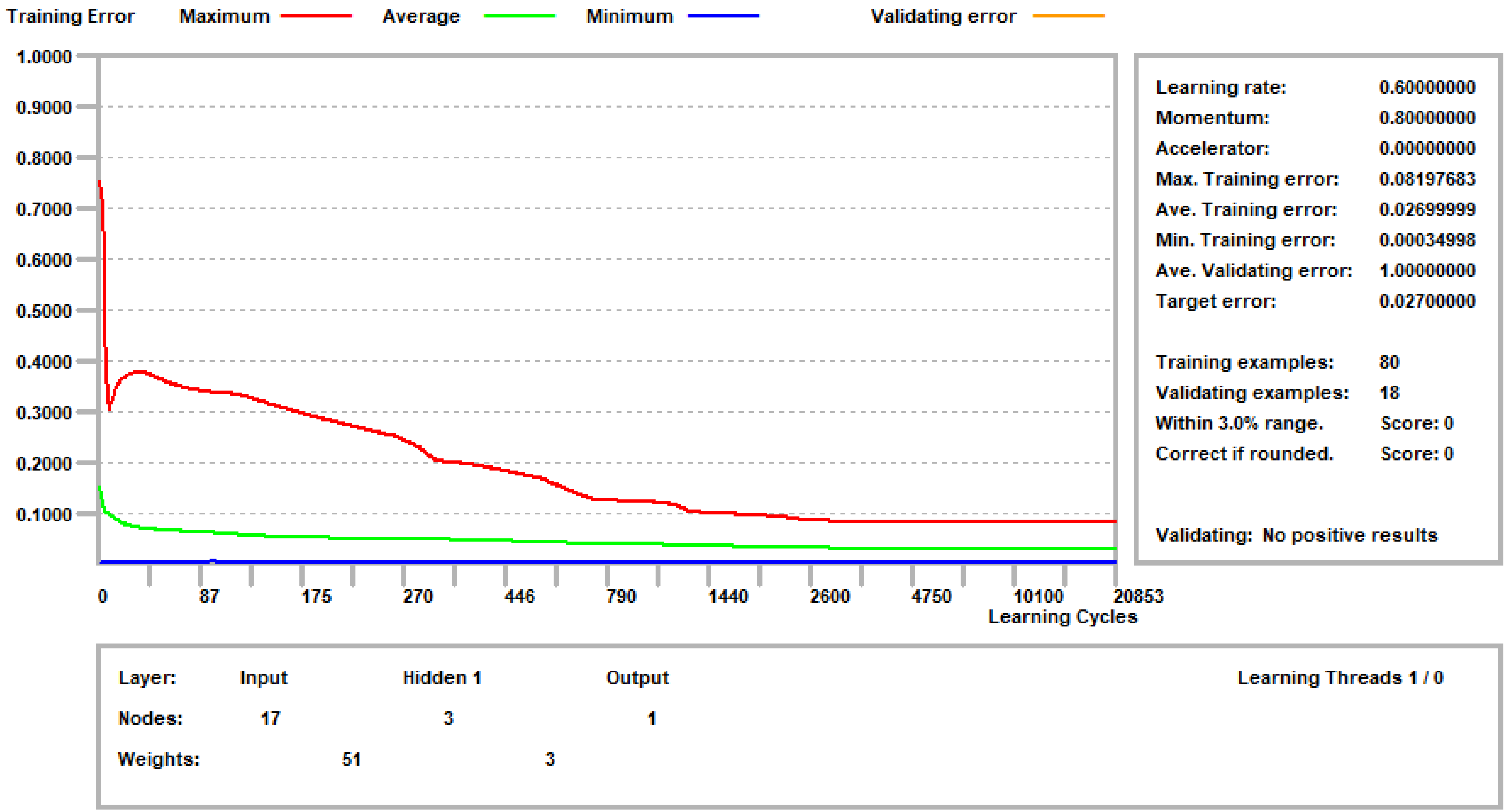
The first option tried for the work involved using a single hidden layer network, with 17 inputs and single output. The hidden layer involved different number of hidden nodes in the single layer. The selected network involved were 17-3-1, 17-4-1, 17-6-1, 17-8-1, 17-10-1 and 17-12-1. Figure 7.13 shows the convergence of the 17-3-1 model showing the training errors i.e. maximum, minimum and average errors. A sensitivity analysis was also carried out for all the models used in the study. Sensitivity plot (Fig. 7.14) shows the sensitivity distribution for the models as mentioned and individual sensitivity of each parameter for the most reliable model i.e. 17-3-1 is shown in ascending order of sensitivity from the most sensitive input (fig.7.15). Table 7.3 shows error calculation for the best suited model i.e. 17-3-1 and Table 7.4 shows the overall statistical analysis.

7.3.4 Four Layer Network

The second option tried for increasing the accuracy of output result was a four layer network involving two hidden layers with varying number of nodes in each of the layers. The networks selected were based on the statistical values obtained in the single hidden layer network and hence started with three nodes in the first hidden layer. The networks used in the work were 17-3-3-1, 17-3-5-1, 17-3-7-1, 17-5-3-1, 17-5-7-1, 17-7-7-1 and 17-9-9-1. Figure 7.16 shows the convergence of the 17-3-3-1 model showing the training errors i.e. maximum, minimum and average errors. The sensitivity plot (Fig. 7.17) shows the sensitivity of various input parameters on the output when using a four layer network. Figure 7.18 shows the sensitivity of the most reliable model in the four layer network i.e. 17-3-3-1, in ascending order. The change of the order of the network causes a change in the order of sensitivity of the input on the output. This shows that the ill posedness of the network i.e. the model parameter do not continuously depend on the variation of the date. This means that even tiny changes in the input observations trigger major variation n the estimated output values. Table 7.5 shows error calculation for the best suited model and Table 7.6 shows the overall statistical analysis for the same model.

Table 7.3 Error Analysis of ANN Model 17 – 3 – 1

Expected % Remediation	Predicted % Remediation	Absolute Error	% Error	Absolute Error Square	R	R^2
0.747	0.802	0.055	7.364	0.005	0.931	0.004
0.711	0.744	0.034	4.728	0.002	0.955	0.001
0.786	0.795	0.009	1.106	0.000	0.989	0.000
0.878	0.887	0.008	0.956	0.000	0.991	0.000
0.879	0.892	0.014	1.536	0.000	0.985	0.000
0.861	0.865	0.003	0.383	0.000	0.996	0.000
0.812	0.781	0.031	3.841	0.001	1.040	0.002
0.739	0.759	0.020	2.761	0.001	0.973	0.000
0.688	0.705	0.017	2.456	0.001	0.976	0.000
0.660	0.727	0.067	10.086	0.010	0.908	0.007
0.722	0.737	0.015	2.106	0.000	0.979	0.000
0.752	0.741	0.011	1.411	0.000	1.014	0.000
0.704	0.741	0.037	5.241	0.003	0.950	0.002
0.726	0.731	0.005	0.661	0.000	0.993	0.000
0.766	0.765	0.001	0.157	0.000	1.002	0.000
0.776	0.817	0.041	5.260	0.003	0.950	0.002
0.668	0.701	0.034	5.063	0.003	0.952	0.002
0.823	0.848	0.025	2.977	0.001	0.971	0.000
0.622	0.655	0.034	5.387	0.003	0.949	0.002
0.879	0.878	0.001	0.137	0.000	1.001	0.000
0.779	0.810	0.031	3.967	0.002	0.962	0.001
0.868	0.886	0.018	2.039	0.000	0.980	0.000
0.859	0.868	0.008	0.978	0.000	0.990	0.000
0.711	0.747	0.036	5.120	0.003	0.951	0.002



Learning rate: 0.60000000
Momentum: 0.80000000
Accelerator: 0.00000000
Max. Training error: 0.08197683
Ave. Training error: 0.02699999
Min. Training error: 0.00034998
Ave. Validating error: 1.00000000
Target error: 0.02700000

Training examples: 80
Validating examples: 18
Within 3.0% range. Score: 0
Correct if rounded. Score: 0

Validating: No positive results

Layer:	Input		Hidden 1		Output	Learning Threads 1 / 0
Nodes:	17		3		1	
Weights:		51		3		

Fig. 7.13 Training Error Plot versus learning cycles (Model 17-3-1)

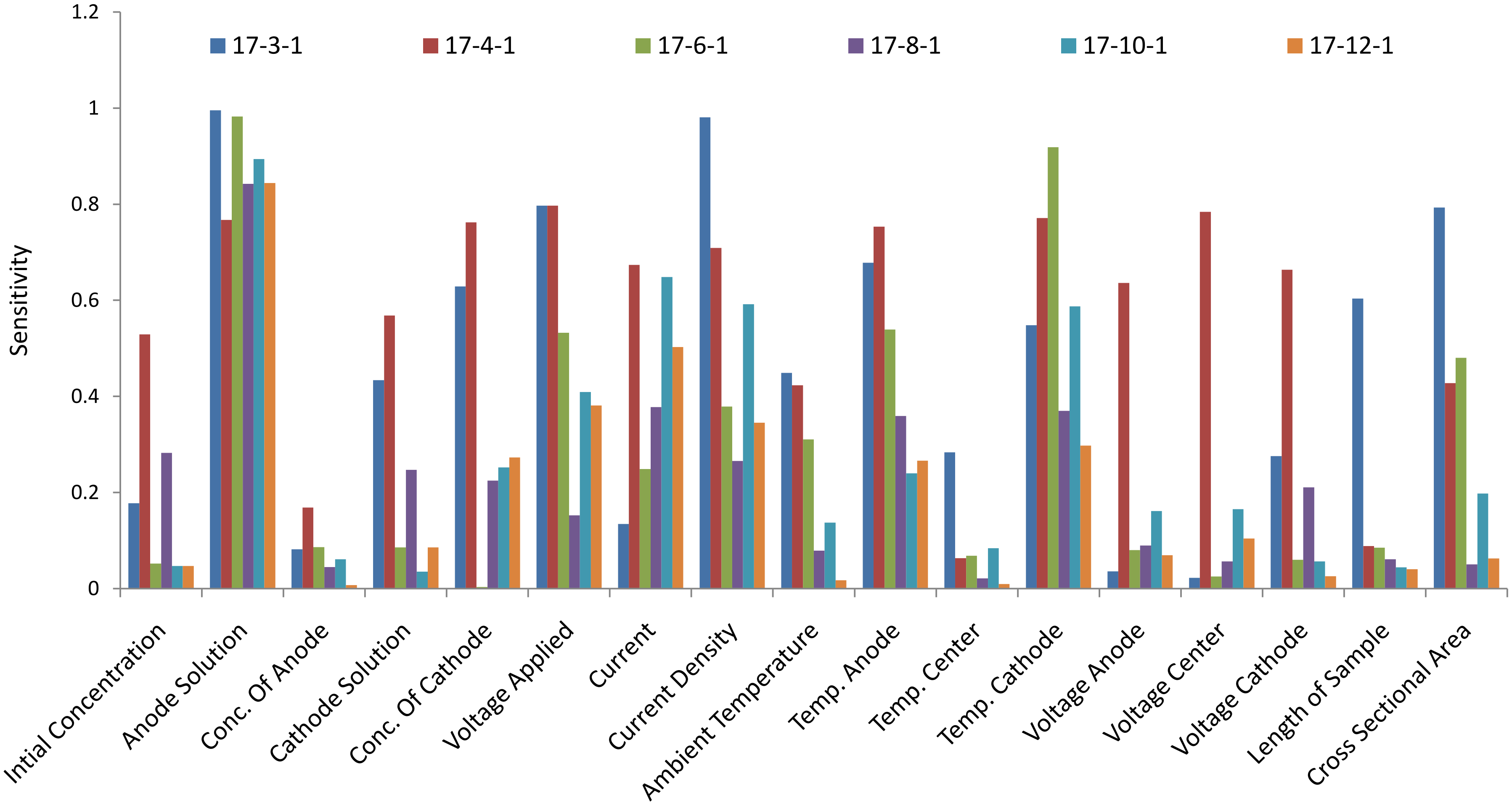


Fig. 7.14 Sensitivity Index for Single Hidden Layer Neural Networks

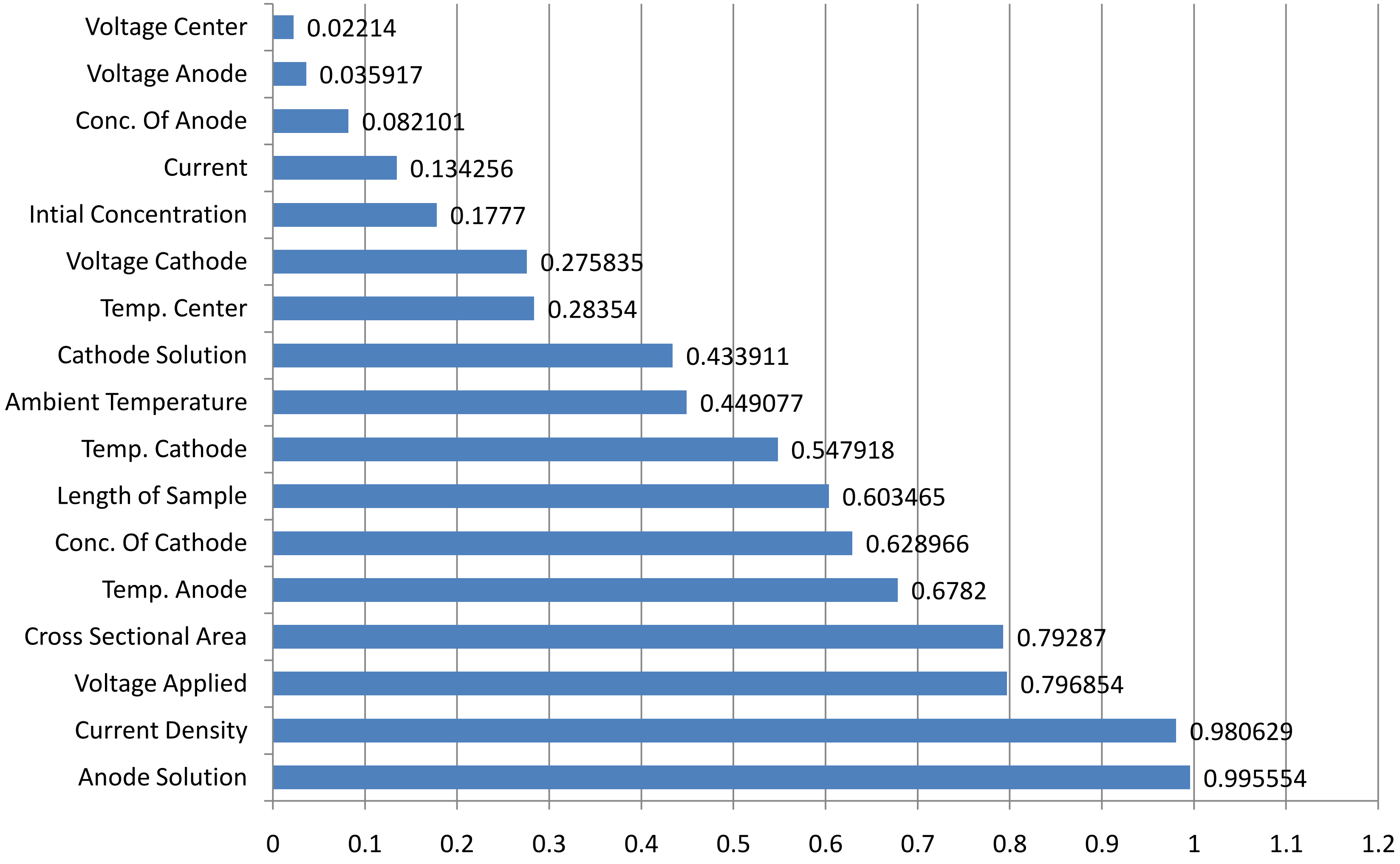


Fig. 7.15 Sensitivity Index for Best Model (17 – 3 – 1)

Table 7.3 Error Analysis of ANN Model 17 – 3 – 1 (Cont'd)

Expected % Remediation	Predicted % Remediation	Absolute Error	% Error	Absolute Error Square	R	R^2
0.664	0.703	0.039	5.875	0.003	0.945	0.002
0.788	0.819	0.032	3.998	0.002	0.962	0.001
0.767	0.417	0.350	45.669	0.209	1.841	0.720
0.892	0.896	0.004	0.471	0.000	0.995	0.000
0.328	0.366	0.038	11.419	0.013	0.898	0.009
0.746	0.797	0.051	6.852	0.005	0.936	0.003
0.875	0.887	0.012	1.326	0.000	0.987	0.000
0.872	0.885	0.013	1.525	0.000	0.985	0.000
0.803	0.843	0.040	5.008	0.003	0.952	0.002
0.898	0.897	0.001	0.111	0.000	1.001	0.000
0.676	0.742	0.066	9.782	0.010	0.911	0.007
0.800	0.893	0.093	11.640	0.014	0.896	0.009
0.834	0.877	0.043	5.191	0.003	0.951	0.002
0.817	0.853	0.036	4.404	0.002	0.958	0.001
0.782	0.846	0.063	8.079	0.007	0.925	0.004
0.765	0.896	0.132	17.222	0.030	0.853	0.019
0.718	0.800	0.082	11.430	0.013	0.897	0.009
0.694	0.760	0.066	9.523	0.009	0.913	0.006
0.742	0.778	0.036	4.850	0.002	0.954	0.001
0.849	0.831	0.019	2.202	0.000	1.023	0.001
0.789	0.865	0.076	9.603	0.009	0.912	0.006
0.703	0.747	0.044	6.305	0.004	0.941	0.003
0.672	0.734	0.063	9.322	0.009	0.915	0.006
0.634	0.712	0.077	12.169	0.015	0.892	0.010
0.611	0.740	0.129	21.091	0.044	0.826	0.028
0.684	0.741	0.058	8.425	0.007	0.922	0.005
0.792	0.865	0.074	9.295	0.009	0.915	0.006
0.737	0.826	0.089	12.085	0.015	0.892	0.010
0.803	0.545	0.258	32.171	0.103	1.474	0.233
0.874	0.897	0.023	2.598	0.001	0.975	0.000
0.790	0.824	0.034	4.252	0.002	0.959	0.001
0.689	0.743	0.053	7.732	0.006	0.928	0.004
0.704	0.737	0.033	4.660	0.002	0.955	0.001
0.701	0.744	0.042	6.046	0.004	0.943	0.002
0.653	0.721	0.068	10.371	0.011	0.906	0.007
0.645	0.697	0.052	8.097	0.007	0.925	0.004
0.783	0.832	0.049	6.244	0.004	0.941	0.003
0.722	0.762	0.041	5.626	0.003	0.947	0.002
0.791	0.839	0.048	6.027	0.004	0.943	0.002
0.881	0.895	0.014	1.532	0.000	0.985	0.000
0.775	0.804	0.028	3.624	0.001	0.965	0.001
0.814	0.842	0.028	3.3767	0.0011	0.9673	0.0006

Table 7.3 Error Analysis of ANN Model 17 – 3 – 1 (Cont'd)

Expected % Remediation	Predicted % Remediation	Absolute Error	% Error	Absolute Error Square	R	R^2
0.887	0.894	0.007	0.733	0.000	0.993	0.000
0.870	0.897	0.027	3.068	0.001	0.970	0.000
0.781	0.815	0.034	4.302	0.002	0.959	0.001
0.679	0.481	0.198	29.184	0.085	1.412	0.176
0.869	0.888	0.018	2.117	0.000	0.979	0.000
0.789	0.792	0.002	0.304	0.000	0.997	0.000
0.859	0.877	0.018	2.107	0.000	0.979	0.000
0.849	0.846	0.003	0.330	0.000	1.003	0.000
0.722	0.772	0.050	6.927	0.005	0.935	0.003
0.892	0.886	0.006	0.639	0.000	1.006	0.000
0.889	0.889	0.000	0.045	0.000	1.000	0.000
0.832	0.854	0.022	2.668	0.001	0.974	0.000
0.756	0.777	0.021	2.752	0.001	0.973	0.000
0.712	0.729	0.017	2.359	0.001	0.977	0.000
0.678	0.721	0.043	6.296	0.004	0.941	0.003
0.661	0.690	0.028	4.264	0.002	0.959	0.001
0.713	0.737	0.024	3.410	0.001	0.967	0.001
0.670	0.693	0.023	3.373	0.001	0.967	0.001
0.654	0.675	0.020	3.118	0.001	0.970	0.000
0.713	0.657	0.056	7.800	0.006	1.085	0.009
0.744	0.741	0.004	0.484	0.000	1.005	0.000
0.699	0.712	0.013	1.873	0.000	0.982	0.000
0.753	0.741	0.013	1.659	0.000	1.017	0.001
0.762	0.740	0.022	2.862	0.001	1.029	0.001
0.833	0.767	0.066	7.886	0.006	1.086	0.009
0.697	0.693	0.004	0.517	0.000	1.005	0.000
0.399	0.404	0.005	1.227	0.000	0.988	0.000
0.404	0.406	0.002	0.495	0.000	0.995	0.000
0.374	0.333	0.042	11.191	0.013	1.126	0.018
0.619	0.625	0.006	0.969	0.000	0.990	0.000
0.898	0.896	0.002	0.245	0.000	1.002	0.000
0.328	0.334	0.006	1.827	0.000	0.982	0.000

Table 7.4 Overall Statistical Analysis of 17 – 3 – 1 Model

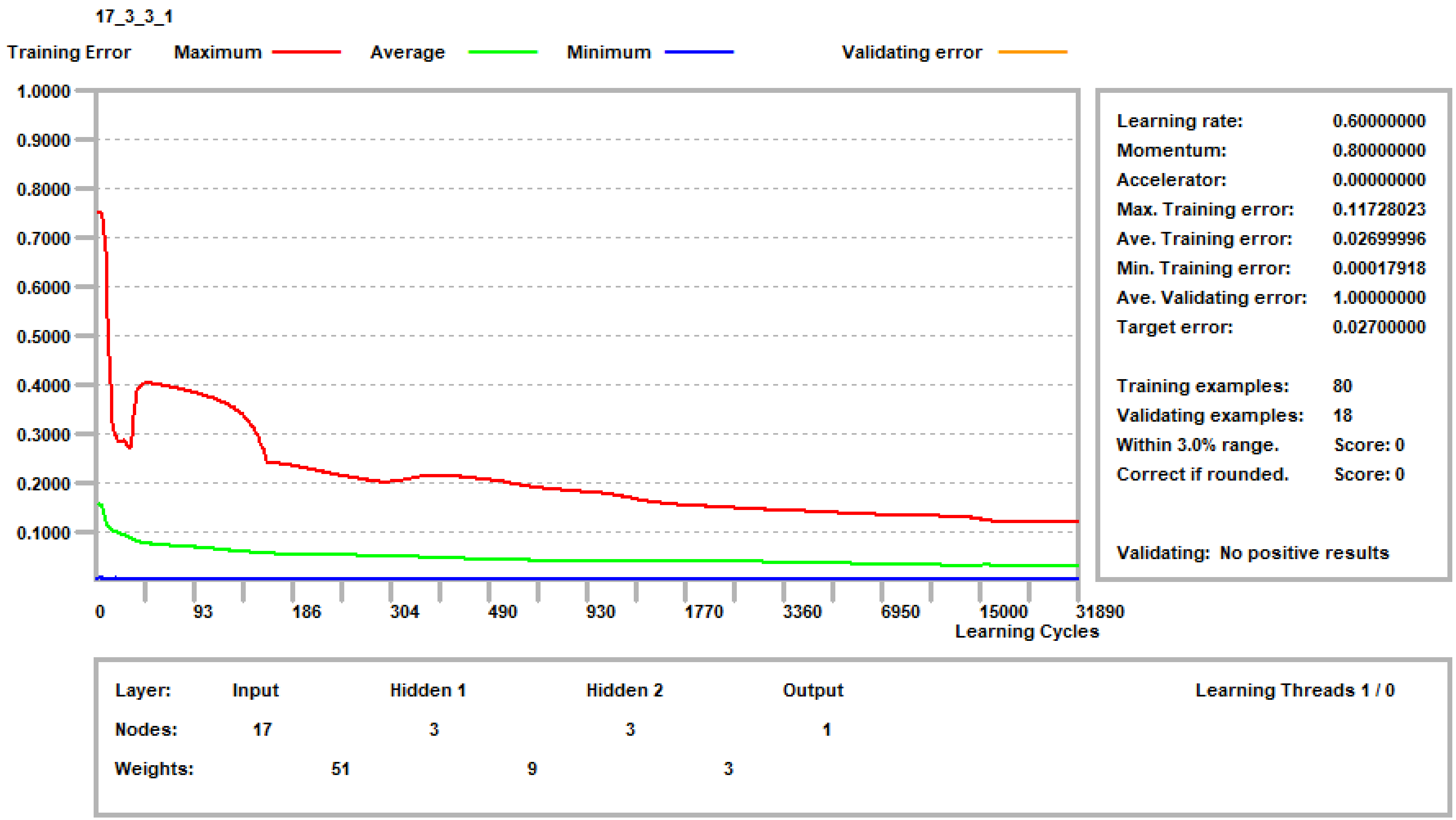
	No. of Sets	Maximum	Minimum	Average
% error	98	45.669	0.045	5.612
Root Mean Square	98	0.0877		
Confidence R	98	0.992		
Scatter σ	98	0.119		

7.3.5 Five Layer Network

The third option tried for increasing the accuracy of results and to bring it to as near as real as possible was a five layer network involving three hidden layers with varying number of nodes in each of the layers. The networks selected were based on the statistical values obtained in the single hidden layer and double hidden layer network and hence started with three nodes in the first and second hidden layer. The networks used in the work were 17-3-3-3-1, 17-3-3-5-1, 17-5-3-3-1, 17-5-5-3-1, 17-3-5-3-1, 17-5-5-5-1 and 17-7-7-7-1. Figure 7.19 shows the convergence of the 17-3-3-3-1 model showing the training errors i.e. maximum, minimum and average errors. The sensitivity plot (Fig. 7.20) shows the sensitivity of various input parameters on the output when using a five layer network. Figure 7.21 shows the sensitivity of the most reliable model in the four layer network i.e. 17-3-3-3-1, in ascending order. It is again visible that the order of input variables affecting the model changes in this case too compared to the earlier two configurations of models i.e. three and four layer models. Table 7.7 shows error calculation for the best suited model and Table 7.8 shows the overall statistical analysis for the same model. To study this sensitivity change a comparative plot for all the three most reliable models from each of the configurations is plotted in Figure 7.22 whereas all the models are compared with respected to errors in output variable as well as R^2 and sigma values in Table 7.9.

Table 7.5 Error Analysis of ANN Model 17 – 3 – 3 – 1

Expected % Remediation	Predicted % Remediation	Absolute Error	% Error	Absolute Error Square	R	R^2
0.747	0.854	0.108	14.393	0.021	0.874	0.007
0.711	0.832	0.121	17.040	0.029	0.854	0.011
0.786	0.853	0.066	8.418	0.007	0.922	0.001
0.878	0.896	0.017	1.947	0.000	0.981	0.001
0.879	0.856	0.023	2.617	0.001	1.027	0.005
0.861	0.890	0.029	3.332	0.001	0.968	0.000
0.812	0.875	0.063	7.695	0.006	0.929	0.001
0.739	0.849	0.110	14.916	0.022	0.870	0.008
0.688	0.833	0.145	21.017	0.044	0.826	0.017
0.660	0.805	0.145	21.960	0.048	0.820	0.019
0.722	0.836	0.114	15.794	0.025	0.864	0.009
0.752	0.835	0.083	11.098	0.012	0.900	0.003
0.704	0.830	0.126	17.924	0.032	0.848	0.012
0.726	0.839	0.113	15.604	0.024	0.865	0.008
0.766	0.853	0.087	11.366	0.013	0.898	0.004
0.776	0.883	0.108	13.858	0.019	0.878	0.006
0.668	0.831	0.163	24.476	0.060	0.803	0.024
0.823	0.880	0.057	6.925	0.005	0.935	0.000
0.622	0.763	0.141	22.689	0.051	0.815	0.020
0.879	0.855	0.024	2.685	0.001	1.028	0.005
0.779	0.867	0.088	11.311	0.013	0.898	0.003



Learning rate: 0.60000000
Momentum: 0.80000000
Accelerator: 0.00000000
Max. Training error: 0.11728023
Ave. Training error: 0.02699996
Min. Training error: 0.00017918
Ave. Validating error: 1.00000000
Target error: 0.02700000

Training examples: 80
Validating examples: 18
Within 3.0% range. Score: 0
Correct if rounded. Score: 0

Validating: No positive results

Layer:	Input	Hidden 1	Hidden 2	Output
Nodes:	17	3	3	1
Weights:	51	9	3	

Learning Threads 1 / 0

Fig. 7.16 Training Error Plot versus learning cycles (Model 17 – 3 – 3 – 1)

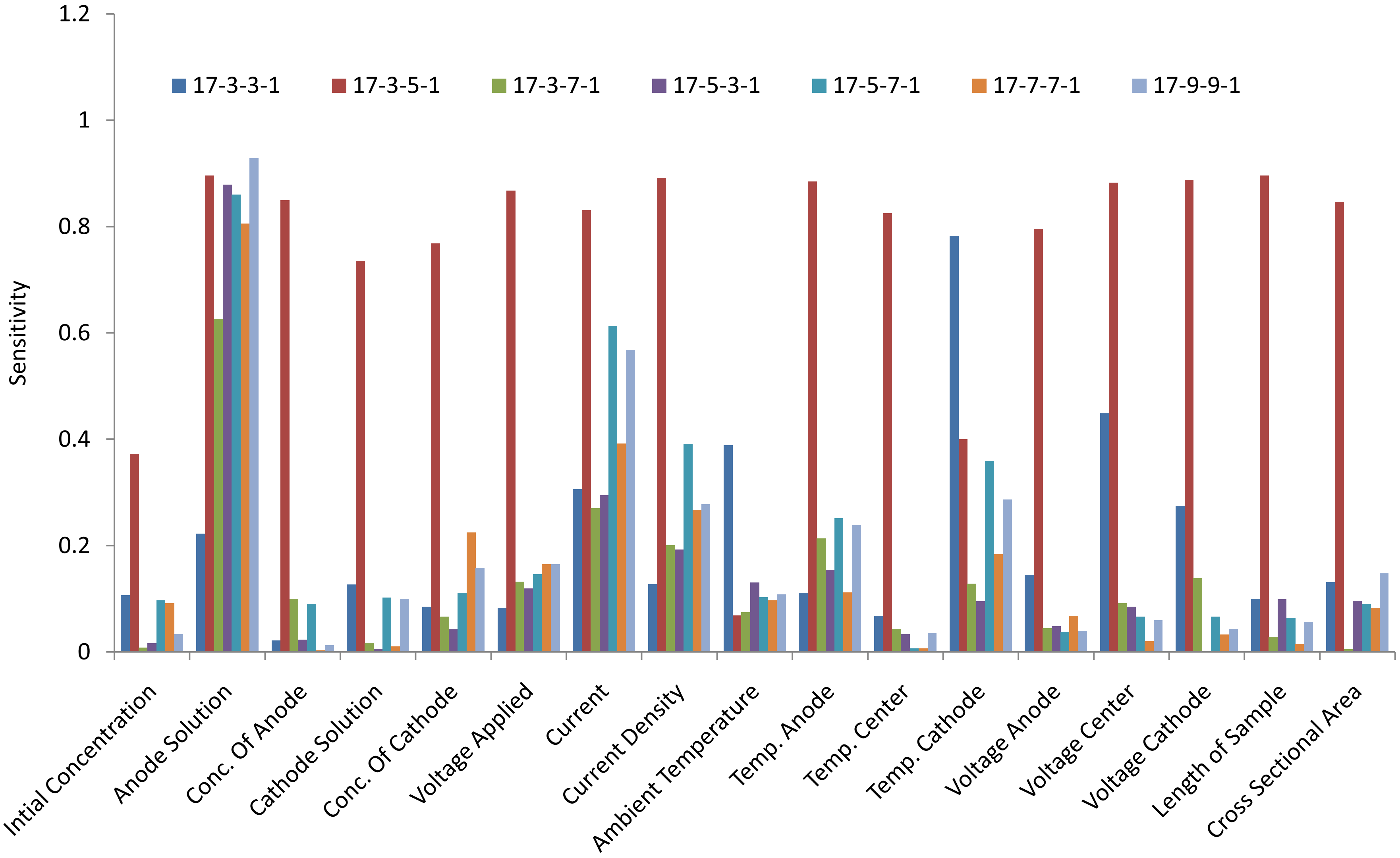


Fig. 7.17 Sensitivity Index for Double Hidden Layer Neural Networks

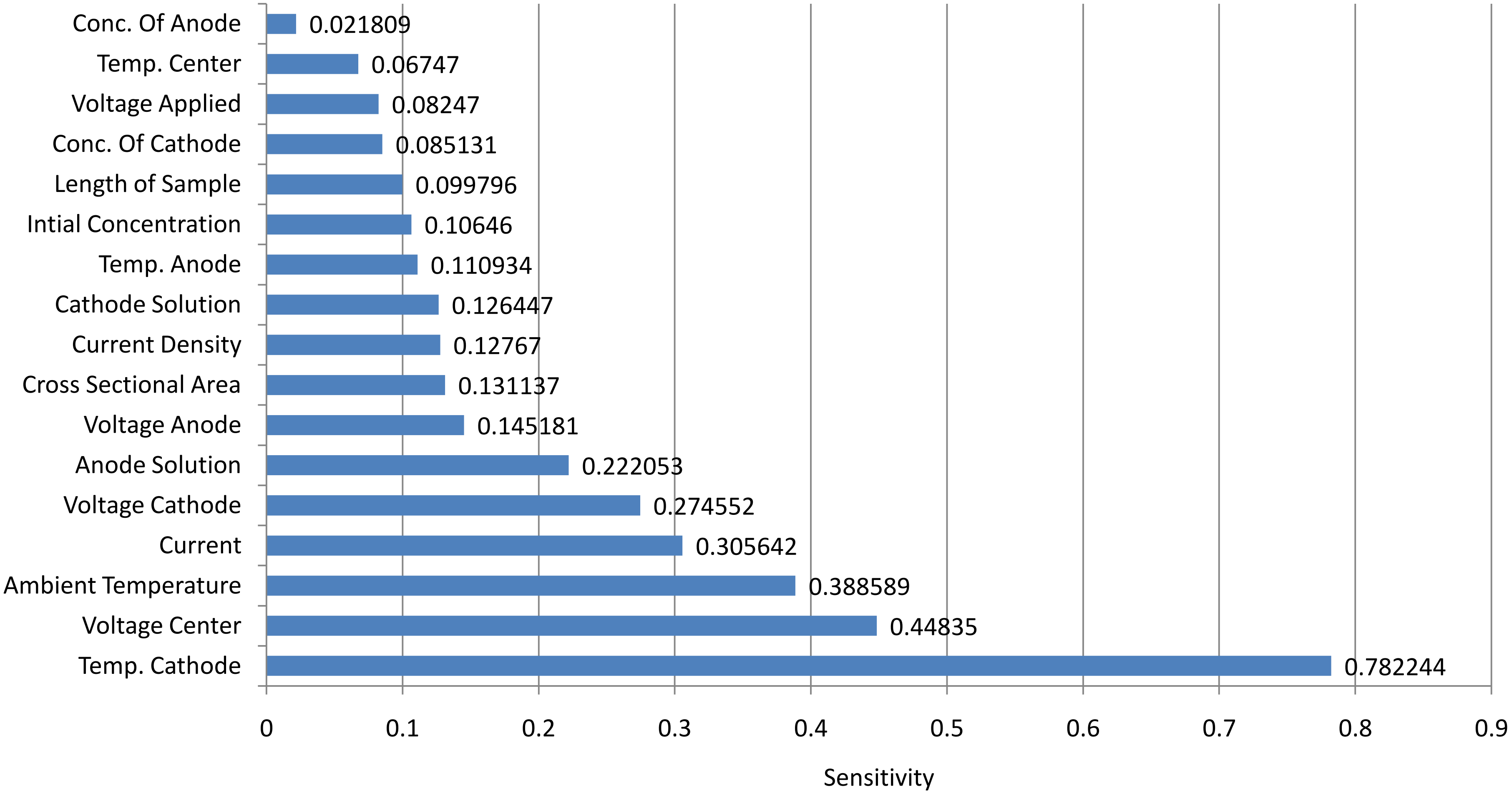


Fig. 7.18 Sensitivity Index for Best Model (17 – 3 – 3 – 1)

Table 7.5 Error Analysis of ANN Model 17 – 3 – 3 – 1 (Cont’d)

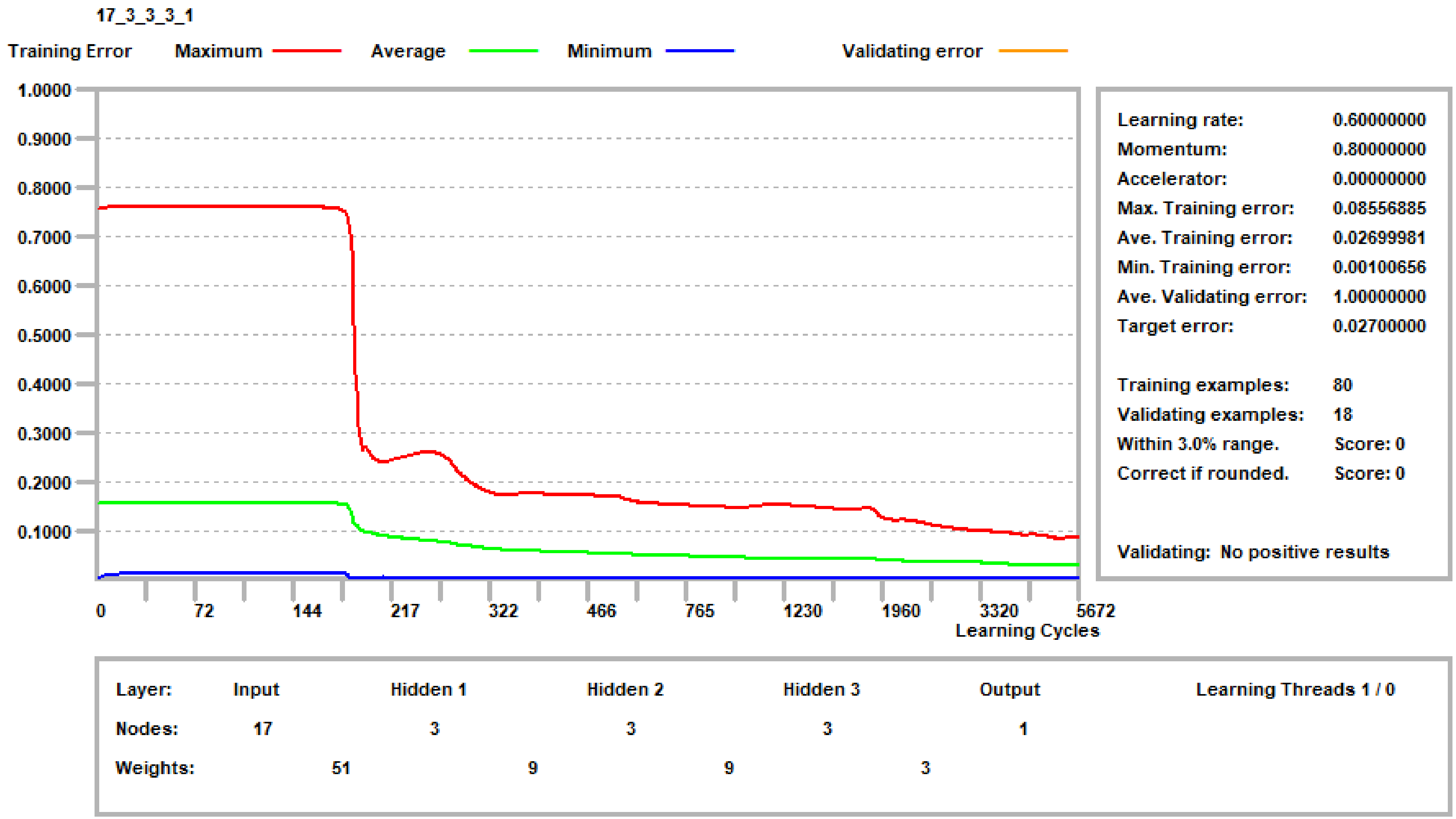
Expected % Remediation	Predicted % Remediation	Absolute Error	% Error	Absolute Error Square	R	R^2
0.868	0.891	0.023	2.649	0.001	0.974	0.000
0.859	0.890	0.031	3.619	0.001	0.965	0.000
0.711	0.835	0.124	17.454	0.030	0.851	0.011
0.664	0.808	0.144	21.738	0.047	0.821	0.018
0.788	0.867	0.080	10.090	0.010	0.908	0.002
0.767	0.761	0.006	0.770	0.000	1.008	0.003
0.892	0.895	0.003	0.325	0.000	0.997	0.002
0.328	0.449	0.121	36.724	0.135	0.731	0.051
0.746	0.847	0.101	13.556	0.018	0.881	0.006
0.875	0.855	0.020	2.297	0.001	1.024	0.004
0.872	0.892	0.020	2.294	0.001	0.978	0.000
0.803	0.879	0.076	9.505	0.009	0.913	0.002
0.898	0.895	0.003	0.278	0.000	1.003	0.002
0.676	0.823	0.147	21.755	0.047	0.821	0.018
0.800	0.895	0.095	11.928	0.014	0.893	0.004
0.834	0.889	0.055	6.582	0.004	0.938	0.000
0.817	0.890	0.073	8.906	0.008	0.918	0.002
0.782	0.875	0.093	11.875	0.014	0.894	0.004
0.765	0.889	0.124	16.268	0.026	0.860	0.009
0.718	0.838	0.119	16.623	0.028	0.857	0.010
0.694	0.837	0.143	20.545	0.042	0.830	0.016
0.742	0.841	0.098	13.229	0.018	0.883	0.005
0.849	0.862	0.012	1.448	0.000	0.986	0.001
0.789	0.872	0.083	10.478	0.011	0.905	0.003
0.703	0.835	0.133	18.859	0.036	0.841	0.013
0.672	0.810	0.138	20.566	0.042	0.829	0.016
0.634	0.770	0.136	21.375	0.046	0.824	0.018
0.611	0.833	0.223	36.466	0.133	0.733	0.050
0.684	0.836	0.153	22.305	0.050	0.818	0.019
0.792	0.855	0.063	7.969	0.006	0.926	0.001
0.737	0.849	0.112	15.219	0.023	0.868	0.008
0.803	0.844	0.040	5.030	0.003	0.952	0.000
0.874	0.895	0.021	2.380	0.001	0.977	0.000
0.790	0.865	0.075	9.452	0.009	0.914	0.002
0.689	0.825	0.136	19.716	0.039	0.835	0.015
0.704	0.820	0.116	16.539	0.027	0.858	0.010
0.701	0.836	0.134	19.136	0.037	0.839	0.014
0.653	0.789	0.136	20.818	0.043	0.828	0.017
0.645	0.763	0.119	18.412	0.034	0.845	0.013
0.783	0.850	0.067	8.555	0.007	0.921	0.001
0.722	0.847	0.125	17.306	0.030	0.852	0.011
0.791	0.851	0.059	7.506	0.006	0.930	0.001
0.881	0.895	0.014	1.588	0.000	0.984	0.001
0.8144	0.836	0.0216	2.65226	0.0007	0.97416	0.00029

Table 7.5 Error Analysis of ANN Model 17 – 3 – 3 – 1 (Cont'd)

Expected % Remediation	Predicted % Remediation	Absolute Error	% Error	Absolute Error Square	R	R^2
0.775	0.836	0.060	7.777	0.006	0.928	0.001
0.887	0.896	0.008	0.924	0.000	0.991	0.001
0.870	0.895	0.024	2.792	0.001	0.973	0.000
0.781	0.867	0.086	11.023	0.012	0.901	0.003
0.679	0.747	0.068	10.047	0.010	0.909	0.002
0.869	0.894	0.025	2.876	0.001	0.972	0.000
0.789	0.837	0.047	5.980	0.004	0.944	0.000
0.859	0.893	0.034	3.981	0.002	0.962	0.000
0.849	0.874	0.024	2.874	0.001	0.972	0.000
0.722	0.803	0.082	11.305	0.013	0.898	0.003
0.892	0.894	0.003	0.280	0.000	0.997	0.002
0.889	0.892	0.003	0.281	0.000	0.997	0.002
0.832	0.866	0.034	4.098	0.002	0.961	0.000
0.756	0.813	0.058	7.621	0.006	0.929	0.001
0.712	0.762	0.050	7.034	0.005	0.934	0.001
0.678	0.756	0.078	11.427	0.013	0.897	0.004
0.661	0.741	0.080	12.050	0.015	0.892	0.004
0.713	0.764	0.052	7.269	0.005	0.932	0.001
0.670	0.733	0.063	9.327	0.009	0.915	0.002
0.654	0.718	0.064	9.705	0.009	0.912	0.002
0.713	0.761	0.048	6.692	0.004	0.937	0.000
0.744	0.762	0.018	2.392	0.001	0.977	0.000
0.699	0.764	0.064	9.209	0.008	0.916	0.002
0.753	0.765	0.012	1.580	0.000	0.984	0.001
0.762	0.764	0.002	0.249	0.000	0.998	0.002
0.833	0.846	0.013	1.500	0.000	0.985	0.001
0.697	0.722	0.026	3.661	0.001	0.965	0.000
0.399	0.409	0.010	2.454	0.001	0.976	0.000
0.404	0.399	0.006	1.434	0.000	1.015	0.003
0.374	0.370	0.004	1.175	0.000	1.012	0.003
0.619	0.634	0.015	2.455	0.001	0.976	0.000
0.898	0.836	0.062	6.927	0.005	1.074	0.014
0.328	0.343	0.014	4.385	0.002	0.958	0.000
0.747	0.854	0.108	14.393	0.021	0.874	0.007
0.711	0.832	0.121	17.040	0.029	0.854	0.011

Table 7.6 Overall Statistical Analysis of 17 – 3 – 3 – 1 Model

	No. of Sets	Maximum	Minimum	Average
% error	98	36.724	0.249	10.129
Root Mean Square	98	0.128		
Confidence R	98	0.957		
Scatter σ	98	0.079		



Learning rate: 0.60000000
Momentum: 0.80000000
Accelerator: 0.00000000
Max. Training error: 0.08556885
Ave. Training error: 0.02699981
Min. Training error: 0.00100656
Ave. Validating error: 1.00000000
Target error: 0.02700000

Training examples: 80
Validating examples: 18
Within 3.0% range. Score: 0
Correct if rounded. Score: 0

Validating: No positive results

Layer: Input Hidden 1 Hidden 2 Hidden 3 Output Learning Threads 1 / 0
Nodes: 17 3 3 3 1
Weights: 51 9 9 3

Fig. 7.19 Training Error Plot versus learning cycles (Model 17 – 3 – 3 – 3 – 1)

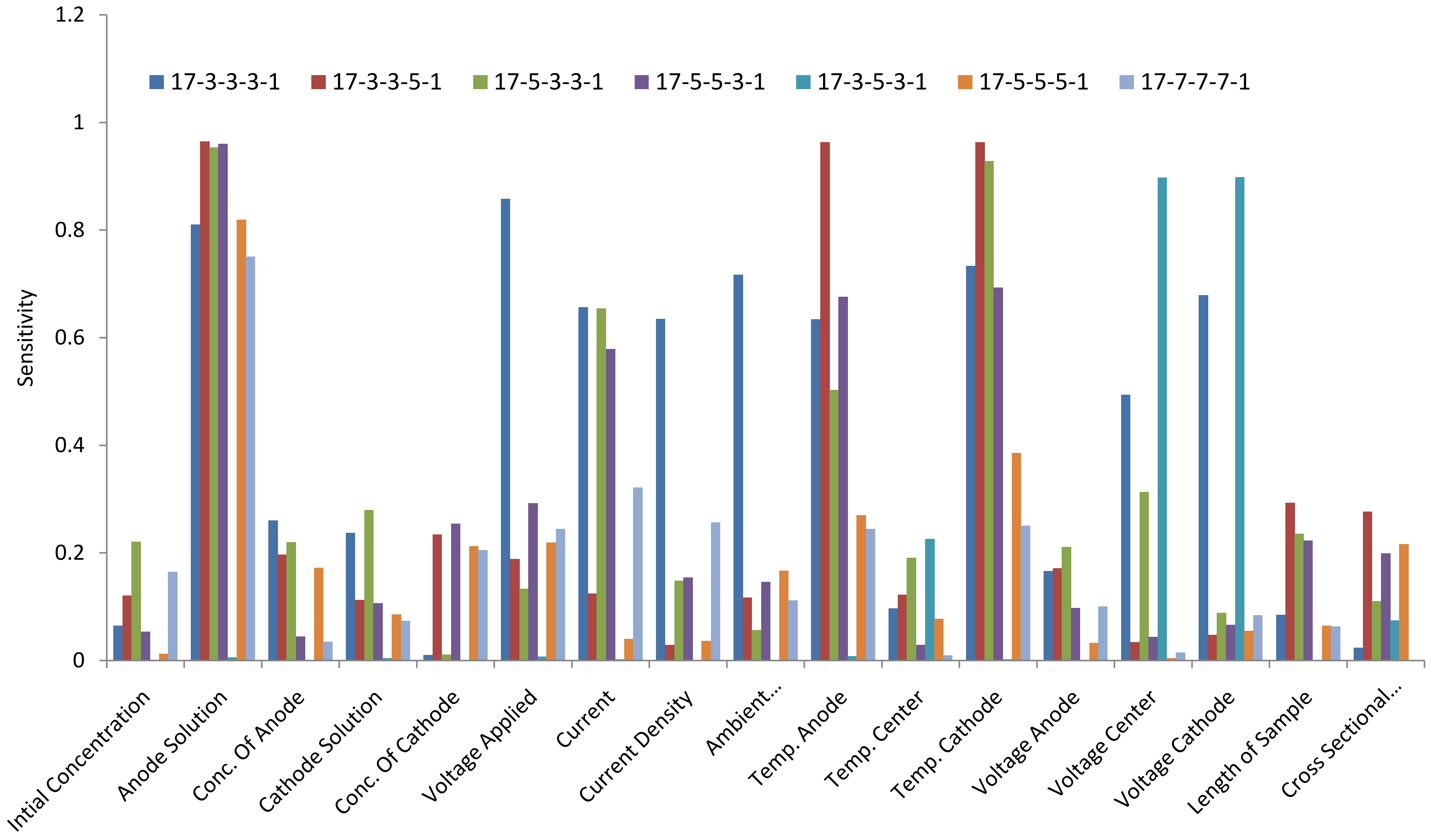


Fig. 7.20 Sensitivity Index for Triple Hidden Layer Neural Networks

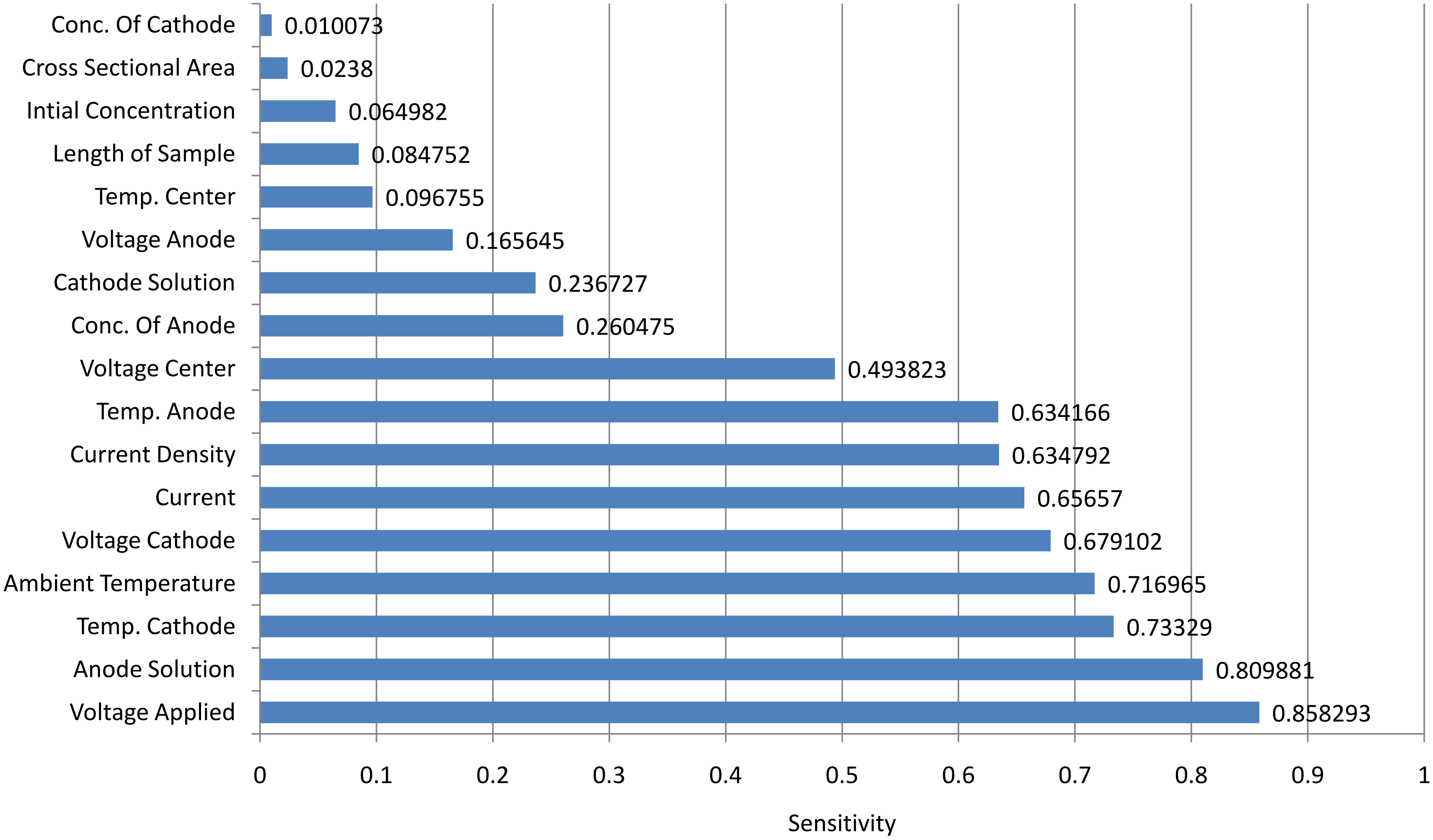


Fig. 7.21 Sensitivity Index for Best Model (17 – 3 – 3 – 3 – 1)

Table 7.7 Error Analysis of ANN Model 17 – 3 – 3 – 3 – 1

Expected % Remediation	Predicted % Remediation	Absolute Error	% Error	Absolute Error Square	R	R^2
0.747	0.728	0.019	2.597	0.001	1.027	0.001
0.711	0.650	0.061	8.569	0.007	1.094	0.010
0.786	0.760	0.026	3.344	0.001	1.035	0.002
0.878	0.866	0.012	1.389	0.000	1.014	0.000
0.879	0.869	0.010	1.104	0.000	1.011	0.000
0.861	0.860	0.001	0.128	0.000	1.001	0.000
0.812	0.792	0.020	2.475	0.001	1.025	0.001
0.739	0.716	0.023	3.086	0.001	1.032	0.001
0.688	0.688	0.000	0.029	0.000	1.000	0.000
0.660	0.697	0.037	5.573	0.003	0.947	0.002
0.722	0.705	0.017	2.383	0.001	1.024	0.001
0.752	0.726	0.026	3.393	0.001	1.035	0.002
0.704	0.739	0.035	4.900	0.002	0.953	0.002
0.726	0.724	0.002	0.317	0.000	1.003	0.000
0.766	0.767	0.001	0.104	0.000	0.999	0.000
0.776	0.782	0.006	0.761	0.000	0.992	0.000
0.668	0.690	0.022	3.355	0.001	0.968	0.001
0.823	0.867	0.044	5.309	0.003	0.950	0.002
0.622	0.650	0.028	4.551	0.002	0.956	0.001
0.879	0.864	0.015	1.650	0.000	1.017	0.001
0.779	0.808	0.030	3.787	0.001	0.964	0.001
0.868	0.862	0.007	0.749	0.000	1.008	0.000
0.859	0.851	0.009	0.989	0.000	1.010	0.000
0.711	0.741	0.030	4.191	0.002	0.960	0.001
0.664	0.716	0.052	7.834	0.006	0.927	0.004
0.788	0.827	0.039	4.988	0.002	0.952	0.002
0.767	0.477	0.290	37.803	0.143	1.608	0.377
0.892	0.892	0.000	0.045	0.000	1.000	0.000
0.328	0.344	0.015	4.689	0.002	0.955	0.001
0.746	0.773	0.027	3.660	0.001	0.965	0.001
0.875	0.883	0.008	0.960	0.000	0.990	0.000
0.872	0.882	0.010	1.158	0.000	0.989	0.000
0.803	0.826	0.024	2.940	0.001	0.971	0.000
0.898	0.891	0.007	0.757	0.000	1.008	0.000
0.676	0.733	0.057	8.450	0.007	0.922	0.005
0.800	0.893	0.093	11.615	0.013	0.896	0.010
0.834	0.863	0.029	3.453	0.001	0.967	0.001
0.817	0.854	0.037	4.490	0.002	0.957	0.001
0.782	0.823	0.041	5.241	0.003	0.950	0.002
0.765	0.859	0.094	12.279	0.015	0.891	0.011
0.718	0.808	0.089	12.446	0.015	0.889	0.011
0.694	0.768	0.074	10.632	0.011	0.904	0.008
0.742	0.794	0.052	6.965	0.005	0.935	0.003

Table 7.7 Error Analysis of ANN Model 17 – 3 – 3 – 3 – 1 (Cont'd)

Expected % Remediation	Predicted % Remediation	Absolute Error	% Error	Absolute Error Square	R	R^2
0.849	0.757	0.093	10.893	0.012	1.122	0.017
0.789	0.851	0.062	7.830	0.006	0.927	0.004
0.703	0.739	0.036	5.138	0.003	0.951	0.002
0.672	0.747	0.075	11.199	0.013	0.899	0.009
0.634	0.740	0.106	16.661	0.028	0.857	0.019
0.611	0.743	0.133	21.729	0.047	0.821	0.030
0.684	0.740	0.056	8.176	0.007	0.924	0.005
0.792	0.836	0.045	5.633	0.003	0.947	0.002
0.737	0.795	0.058	7.839	0.006	0.927	0.004
0.803	0.541	0.262	32.595	0.106	1.484	0.240
0.874	0.891	0.017	1.968	0.000	0.981	0.000
0.790	0.844	0.053	6.732	0.005	0.937	0.003
0.689	0.740	0.051	7.370	0.005	0.931	0.004
0.704	0.745	0.041	5.840	0.003	0.945	0.002
0.701	0.738	0.037	5.262	0.003	0.950	0.002
0.653	0.733	0.080	12.316	0.015	0.890	0.011
0.645	0.689	0.044	6.809	0.005	0.936	0.003
0.783	0.794	0.011	1.366	0.000	0.987	0.000
0.722	0.778	0.057	7.843	0.006	0.927	0.004
0.791	0.824	0.032	4.094	0.002	0.961	0.001
0.881	0.868	0.014	1.577	0.000	1.016	0.001
0.814	0.836	0.021	2.628	0.001	0.974	0.000
0.775	0.801	0.025	3.250	0.001	0.969	0.001
0.887	0.876	0.011	1.274	0.000	1.013	0.000
0.870	0.884	0.013	1.540	0.000	0.985	0.000
0.781	0.796	0.015	1.895	0.000	0.981	0.000
0.679	0.712	0.033	4.906	0.002	0.953	0.002
0.869	0.865	0.004	0.506	0.000	1.005	0.000
0.789	0.773	0.017	2.090	0.000	1.021	0.001
0.859	0.862	0.003	0.326	0.000	0.997	0.000
0.849	0.855	0.005	0.636	0.000	0.994	0.000
0.722	0.732	0.011	1.455	0.000	0.986	0.000
0.892	0.892	0.000	0.045	0.000	1.000	0.000
0.889	0.885	0.005	0.506	0.000	1.005	0.000
0.832	0.837	0.005	0.601	0.000	0.994	0.000
0.756	0.778	0.022	2.924	0.001	0.972	0.000
0.712	0.717	0.005	0.688	0.000	0.993	0.000
0.678	0.683	0.005	0.723	0.000	0.993	0.000
0.661	0.647	0.015	2.207	0.000	1.023	0.001
0.713	0.722	0.010	1.361	0.000	0.987	0.000
0.670	0.715	0.045	6.641	0.004	0.938	0.003
0.654	0.653	0.002	0.275	0.000	1.003	0.000
0.713	0.711	0.002	0.281	0.000	1.003	0.000

Table 7.7 Error Analysis of ANN Model 17 – 3 – 3 – 3 – 1 (Cont'd)

Expected % Remediation	Predicted % Remediation	Absolute Error	% Error	Absolute Error Square	R	R^2
0.744	0.739	0.006	0.739	0.000	1.007	0.000
0.699	0.715	0.015	2.188	0.001	0.979	0.000
0.753	0.735	0.018	2.403	0.001	1.025	0.001
0.762	0.727	0.035	4.634	0.002	1.049	0.003
0.833	0.871	0.038	4.525	0.002	0.957	0.001
0.697	0.688	0.009	1.278	0.000	1.013	0.000
0.399	0.382	0.017	4.258	0.002	1.045	0.003
0.404	0.394	0.011	2.695	0.001	1.028	0.001
0.374	0.438	0.064	17.014	0.029	0.855	0.019
0.619	0.616	0.003	0.436	0.000	1.004	0.000
0.898	0.889	0.009	0.958	0.000	1.010	0.000
0.328	0.338	0.010	2.923	0.001	0.972	0.001
0.747	0.728	0.019	2.597	0.001	1.027	0.001
0.711	0.650	0.061	8.569	0.007	1.094	0.010

Table 7.8 Overall Statistical Analysis of 17 – 3 – 3 – 3 – 1 Model

	No. of Sets	Maximum	Minimum	Average
% error	98	37.803	0.029	4.845
Root Mean Square	98	0.077		
Confidence R	98	0.994		
Scatter σ	98	0.094		

The work for improving the performance of the ANN selected architecture was based on the output parameter error calculations, the maximum and minimum error calculations and the R^2 values; this was by keeping the target error for the network to be 0.02. The output values shown by the network were rounded off to four decimal points for error calculations. Each network selected was run for 100 cycles before using a validating set and each validating set was run for 100 cycles before using the output value for error calculations. Sensitivity analysis of the neural network output with respect to small input perturbations is used to quantify the informativeness of patterns. Only the most informative patterns, which are those patterns closest to decision boundaries, are selected for training. Care must be taken when training perceptron network to ensure that they do not over fit the training data and then fail to generalize well in new situations. So the main purpose of this paper lies in studying the effect of changing both the No of hidden layers of MLPs and the No of processing elements that exist in the hidden layers on the analyzed properties of Jordan Oil Shale. After constructing such a MLP and changing the number of hidden layers, we found that with increasing the number of processing elements in the hidden layers. We reach to an optional output results w.r.t the experimental one or the analytical formulated one. This obtained output is completely matched with the main concepts of theoretical visions of ANN.

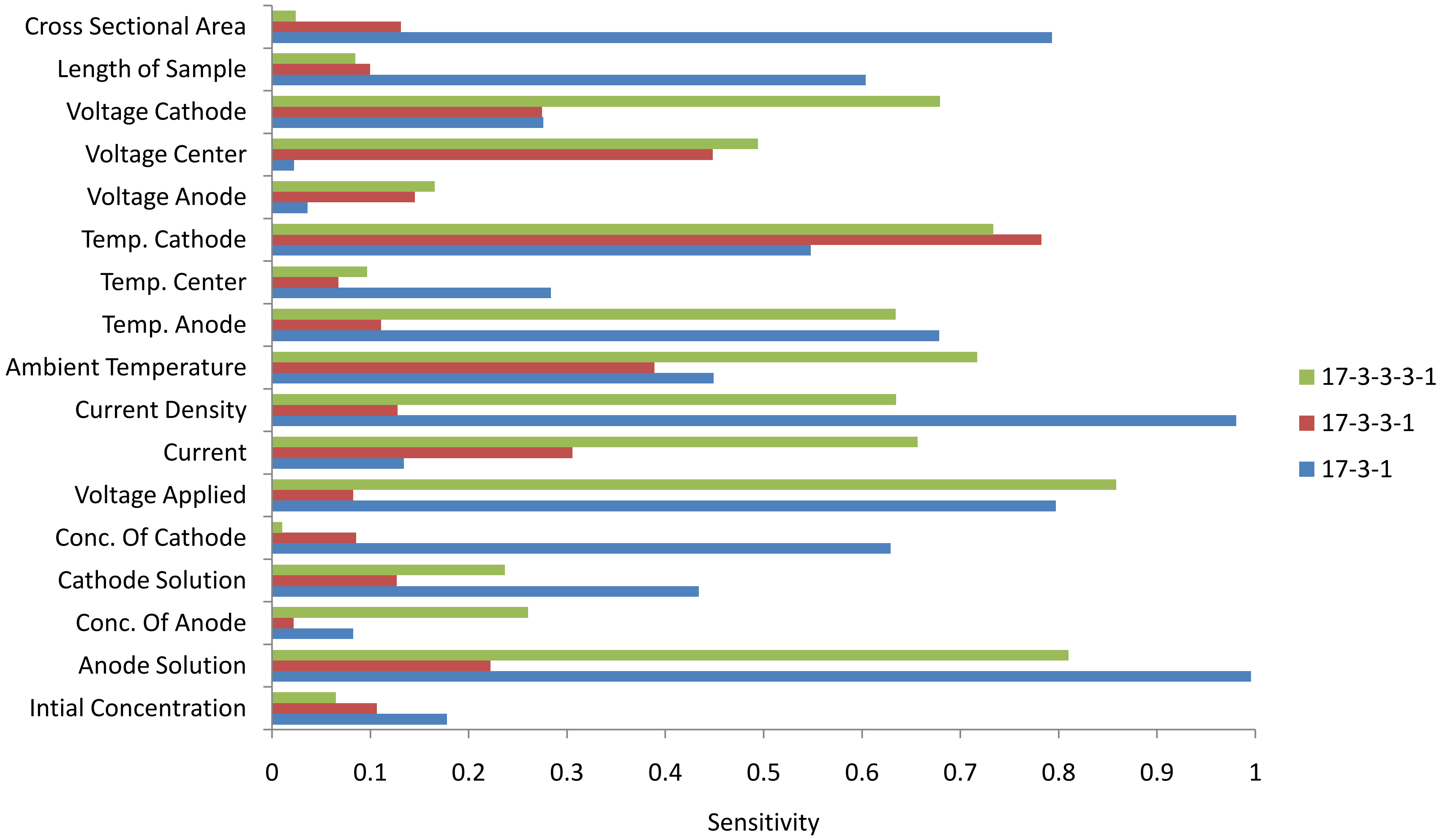


Fig. 7.22 Comparative Sensitivity Index for Three Best Fit Models

Table 7.9 Comparative Statistical Analysis of All Models with Error Percentage

Model No.	Model	Avg. Error (%)	Minimum Error (%)	Maximum Error (%)	RMS Error	Training Cycles	R	Sigma
1	**17,3,1**	**5.6120**	**0.0450**	**45.6692**	**0.0877**	**20853**	**0.9921**	**0.1189**
2	17,4,1	6.4023	0.1200	53.2090	0.0978	3340	0.9884	0.1438
3	17,6,1	9.9686	0.0902	49.2304	0.1255	989	0.9647	0.1259
4	17,8,1	8.4088	0.0000	56.0918	0.1157	790	0.9744	0.1500
5	17,10,1	10.9664	0.1002	39.2121	0.1366	564	0.9577	0.1057
6	17,12,1	9.3378	0.0656	39.9948	0.1209	746	0.9667	0.1037
7	**17,3,3,1**	**10.1289**	**0.2494**	**36.7235**	**0.1281**	**31890**	**0.9572**	**0.0785**
8	17,3,5,1	8.7392	0.3139	67.1474	0.1236	179127	0.9667	0.0856
9	17,3,7,1	9.5552	0.2116	73.8248	0.1358	33933	0.9650	0.1048
10	17,5,3,1	11.5681	0.0112	90.4915	0.1646	993	0.9598	0.1494
11	17,5,7,1	10.2063	0.0112	32.8476	0.1276	1148	0.9597	0.0886
12	17,7,7,1	11.2869	0.1002	55.0897	0.1475	965	0.9588	0.1206
13	17,9,9,1	10.2235	0.1050	69.0438	0.1417	1210	0.9632	0.1191
14	**17,3,3,3,1**	**4.8451**	**0.0291**	**37.8033**	**0.0771**	**5672**	**0.9936**	**0.0942**
15	**17,3,3,5,1**	**5.9881**	**0.0902**	**40.5035**	**0.0825**	**14132**	**0.9827**	**0.0908**
16	17,5,3,3,1	6.6863	0.1619	55.1526	0.0974	1963	0.9798	0.1388
17	17,5,5,3,1	6.9583	0.0000	72.2192	0.1111	1013	1.0298	0.0974
18	17,3,5,3,1	10.9325	0.0569	52.6089	0.1411	327236	0.9620	0.1427
19	17,5,5,5,1	10.3301	0.0336	48.8260	0.1355	1314	0.9671	0.1472
20	17,7,7,7,1	7.2021	0.0797	51.1218	0.1041	763	0.9790	0.1271

It can be clearly seen that the predicted output using the neural network model differed a little with the measured data and the average error was between 4.84% and 11.56%. The relative error calculates accordingly for maximum and minimum error was between 0.0771 and 0.1475. Since the relative error standard for all the models is less than 20% all the models can be used for practical purposes. The multiple regression analysis to the same sequences shows that the absolute error of predicted and measured output gave adjusted R^2 value of 70.5%, which shows that the neural network model has better predicted accuracy with all the models.

CHAPTER 8

Summary of Findings

Summary of Findings

Chapter Eight

8.1 SUMMARY

The purpose of the thesis was to formulate an optimal recipe for the electrokinetic removal of nickel from contaminated soil to be used for field applications. The work also intended to propose the method of electrokinetic as a tool for delivery of chemical grouts in extremely fine soils without any pressure gradient application as well as its use to dewater soft soils using conductive textiles.

The investigation, experimentation as well as result and analysis are described in the study (Chapter 3, 4 and 5) permitted the finding of a suitable combination of purging solutions for heavy metal removal, the most effective mix of grout under a given applied voltage as well as the most efficient conductive textile for dewatering of soil for under given conditions.

The results of the laboratory study carried out were used to validate regression models, developed separately for each of the two processes of electrokinetic remediation of nickel contaminated soil as well as electrokinetic grouting (Chapter 6). The regression model developed for electrokinetic remediation was not found to satisfy the criteria of coefficient of determination, therefore an ANN model structure was developed which gave a very good coefficient of determination (Chapter 7).

8.2 FINDINGS

8.2.1 Electrokinetic Remediation of Nickel Contaminated Soil

- Varying the electrode spacing from 34.50 cm to 91.44 cm with cross sectional area of sample = 20.27sq.cm using 0.1M EDTA as cathodic purging solution and 1M NaCl as anodic purging solution resulted in 87.44% to 66.76% removal efficiency when initial concentration was 250 mg/kg of nickel.
- Under the similar test conditions, the removal efficiency varied from 81.74% to 68.93% for initial nickel concentration of 350 mg/kg.
- The removal efficiency for nickel under the same test conditions varied from 83.21% to 67.88% for initial nickel concentration of 500 mg/kg.
- Change in the cross sectional area of the sample from 20.27 sq. cm. to 81.07 sq. cm, keeping all other parameter constant resulted in the removal efficiency of 87.84% to 76.63% for 250 mg/kg initial concentration
- To look into the energy expenditure, the study was further extended by varying the applied voltage which resulted in increase in the removal efficiency from 71.01% at

8.33 V to 91.43% at 37.50 V with the use of 0.1M EDTA (cathode purging solution) and 1M NaCl (anode purging solution), at an electrode spacing of 34.5 cm for an initial concentration of 250 mg/kg.

- At initial concentration of 350 mg/kg, the efficiency of removal was 83.41% when applied voltage was 37.50 V which reduced to 73.71% at 8.33V, with similar purging solutions, but with the cathode solution being changed to 0.1M Tween 80 with 1M NaCl as the anode solution the removal efficiency varied from 71.49% for 12.50 V to 81.06% for 37.50 V, whereas it dropped down drastically to 57.67% for 12.50 V to 69.70% for 37.50 V, when the cathode solution was 0.1M Igepal CA 720.
- For initial concentration of 500 mg/kg the removal efficiency with 0.1M EDTA and 1M NaCl, varied from 72.17% at applied voltage of 8.33 V to 84.06% at 37.50 V. These removal values showed a radical drop to 34.56% at 8.33 V to 40.44% at 37.50 V when the anode solution was changed to 1M $CaCl_2$ instead of 1M NaCl.
- To formulate a combination of best suited purging solution, varying anode solutions were applied with 0.1M EDTA at an initial nickel concentration of 250 mg/kg, whereby the removal efficiency varied with maximum efficiency of 87.20% being achieved with 1M NaCl to a minimum efficiency of 32.84% being achieved when 1M $CaCl_2$ was used at an applied voltage of 25 V with electrode spacing of 34.5 cm.
- For initial nickel concentration of 250 mg/kg, when the cathode solution was changed over to 1M $NaNO_3$, the efficiency of removal keeping all other parameter constant as mentioned above varied from 69.32% for 1M NaCl anodic solution to 22.17% for 1M $CaCl_2$ as anodic solution.
- With initial nickel concentration of 350 mg/kg, the removal efficiency with 0.1M EDTA as cathode solution was 81.74% for 1M NaCl at anode which reduced down to 65.28% for 1M Butyric Acid at the anode, the values further dropped down to 67.21% for 1M NaCl and 64.47% for 1M Butyric Acid when the cathode solution was changed to 1M $NaNO_3$.
- Contaminated kaolinite with initial nickel concentration of 500 mg/kg followed an almost similar trend. Cathode solution of 0.1M EDTA showed maximum removal efficiency of 86.73% with 1M NaCl and reduced down to a minimum value of 39.93% for 1M $CaCl_2$ solution. When the cathode solution was change to 1M $NaNO_3$ the removal efficiency dropped down to 62.56% for 1M NaCl varying down to 34.59% for 1M $CaCl_2$.
- Variations in cathodic solutions were experimented which showed 87.50% removal efficiency with 0.1MEDTA gradually reducing down to 75.24% with 0.1M Igepal CA 720, with 1M NaCl at the anode and initial nickel concentration of 250 mg/kg with electrode spacing of 34.5 cm with applied voltage of 25 V.
- Initial nickel concentration of 350 mg/kg in the artificially spiked soil, the removal efficiency was 81.74% with 0.1M EDTA varying to 64.38% for 0.1M Igepal CA 720, for anode solution of 1M NaCl for applied voltage of 25V at 34.5 cm electrode spacing.

- Regression modeling carried out for this phase of electrokinetics yielding the following regression model as given below. The model showed an overall adequacy with $R^2 = 0.758$ and adjusted $R^2 = 0.705$ with a standard error of 0.0592.

$$y = 0.71 + 0.018x1 - 0.536x2 + 0.033x3 - 0.051x4 + 0.006x5 + 0.175x6 + 0.084x7 + 0.193x8 + 0.137x9 + 0.325x10 - 0.055x11 - 0.0608x12 - 0.130x13 + 0.211x14 + 0.133x15 - 0.507x16 -0.014x17$$

y= Percentage of removal
x1= Initial Concentration
x2= Anode Solution
x3= Conc. Of Anode
x4= Cathode Solution
x5= Conc. Of Cathode
x6= Voltage Applied
x7= Current
x8= Current Density
x9= Ambient Temperature
x10= Temp. Anode
x11= Temp. Centre
x12= Temp. Cathode
x13= Voltage Anode
x14= Voltage Centre
x15= Voltage Cathode
x16= Length of Sample
x17= Cross Sectional Area

- In order to get form a higher accurate model ANN technique was adopted which gave more accurate models with ANN architecture of 17 – 3 – 1 with R (Coefficient of Determination) of 0.9921 and a sigma value of 0.1189, 17 – 3 – 3 – 1, gives R = 0.9572 and sigma = 0.0785, 17 – 3 – 3 – 3 – 1 responded with R = 0.9936 and sigma = 0.0942, and 17 – 3 – 3 – 5 – 1, showed R = 0.9827 with sigma = 0.0908.

On the whole it can be concluded that increasing the initial concentration, electrode spacing shows decrease in the percentage removal of nickel, whereas increase in applied voltage, increase in cross sectional area of sample and the strength of the purging solutions results in higher percentage removal. Overall chelating agents prove effective as opposed to organic acids and inorganic compounds. The least effective compound turns out to be calcium chloride with any combination of cathode purging solution.

8.2.2 Electrokinetic Grouting for Problematic Soil Stabilization

- The study for electrokinetic grouting was first carried out on six different soils to understand the applicability of the process, keeping in mind the soil particle size. A maximum decrease of 81.00% in the coefficient of permeability was observed in Soil 2, with Soil 1 showing minimum improvement with only about 1.01% reduction in the coefficient of permeability which can be considered negligible, when a 25% sodium silicate and 2% calcium chloride was used as a two component grout at the cathode and anode respectively under a applied voltage of 25V for reactor 4.
- The percentage increase of the unconfined compressive strength for the same set of experiments varied with a maximum increase of 204.55% observed for Soil 4, with the lowest increase of 28.57% for Soil 6.
- The third set of experiments was performed to optimize the experimental duration by varying the soil type and applied voltage also. The experiments performed on Soil 2 showed a the variation in increase of UCS from 76.01% for duration of 70 days to 33.18% for duration of 35 days, the decrease in the coefficient of permeability also showed a similar trend with the value varying from 78.2% decrease for 70 days to

55.54% for 35 days, with 25% SS and 2% $CaCl_2$ with applied voltage of 25V for reactor 4.

- When the same set of experiments was performed for Soil 4, the decrease in the coefficient of permeability varied from 80.15% to 72.54% for experimental duration varying from 70 to 35 days respectively. The corresponding variation in the percentage increase of UCS was 221.25% to 204.55% for duration variation from 70 to 35 days.
- Experimental duration optimization was studied for low voltage to study the trend on Soil 4, by reducing the voltage to 12.5V. The percentage decrease in the coefficient of permeability varied for 138.64% for 35 day duration to 211.71% for 70 day duration.
- For the purpose of lower energy consumption intermittent supply was applied to the next set of experiments with work being carried on Soil 4 using reactor 1, with all other parameters being similar to the above mentioned set. The variation in improvement in UCS was from 54.91% for 1day on/2 day off to a maximum increase of 128.83% reported for continuous supply.
- The percentage decrease in the coefficient of permeability for the above set of experiments followed a similar trend with minimum improvement of 31.72% observed for 1 day on/2 day off to an maximum improvement of 44.63% for continuous supply.
- Grouts are very sensitive to the proportions of hardeners and the mix of each of the components. For the purpose the next set of experiments varied the percentage of calcium chloride from 1 to 2.5% in increments of 0.5% for four different proportions of sodium silicate varying from 15 to 25% in increments of 5%. For 15% and 20% sodium silicate proportions, maximum improvement was observed with 2% calcium chloride i.e. 49.69% and 50.94% for coefficient of permeability decrease and 130.68% and 152.27% for UCS increase respectively.
- The application of applied voltage is affected by the cross sectional area of the soil, for which the set of experiments was carried out keeping all other parameters constant. The improvement in UCS varied from 204.55% for reactor 4 to 23.86% for reactor 1, with corresponding decrease in coefficient of permeability varying from 72.54% to 71.16% for reactor 4 and 1 respectively.
- The next set of experiments was carried out on Soil 1, 2 3 and 4 performed on reactor 4 under applied voltage of 12.5 and 25V with all other parameter as already mentioned above. The maximum improvement was observed for Soil 4, with UCS increase of 204.55% and corresponding coefficient of permeability decrease by 72.54%. The minimum improvement was observed for Soil 1, with decrease in coefficient of permeability of 57.50% and increase in UCS of 57.80%.
- A larger variation of applied voltage from 10.9 to 27.3V was studied on Soil 4 using reactor 2. Application of higher voltage of 27.3V proved beneficial with 90.89% reduction in coefficient of permeability with corresponding increase in UCS of 76.02%, which dropped down to 74.20% and 34.87% respectively for 10.9V.

- The variation in the type of hardener for the sodium silicate grout showed that 3% aluminium sulphate gave the best results with the increase in UCS value of 361.54% and corresponding decrease in the coefficient of permeability of 54.63%.
- To increase the acceptability of the process on field, low frequency AC supply instead of DC supply was tried for a grout mix of 25% sodium silicate with 2% calcium chloride with 5V applied for reactor 1. The improvement for UCS and coefficient of permeability decreased down to 9.45% and 24.1% respectively at 1Hz with the maximum improvement of 37.14% and 30.44% respectively at 0.25Hz.
- Sodium silicate concentration was crucial to be studied on different soils since the viscosity is an important factor for the flow of grout in fine soils. For this the study was carried out on Soil1, 2, 3 and 4 by varying the applied voltage also. The complete work was carried on reactor 4. The maximum improvement was observed using 30% sodium silicate with 2% calcium chloride for all the soils for both applied voltages. The maximum improvement achieved for UCS value was 228.41% for Soil 4 with minimum 59.63% being achieved for Soil 3, with the similar trend maximum decrease of 81.60% for Soil 4 and minimum decrease of 15.23% for Soil 1 was observed for coefficient of permeability.
- Regression modeling carried out for this phase of electrokinetics yielding the following regression model as given below. The model UCS showed an overall adequacy with $R^2 = 0.778$ and adjusted $R^2 = 0.740$ with a standard error of 0.0490. Model k showed an overall adequacy with $R^2 = 0.683$ and adjusted $R^2 = 0.628$ with a standard error of 0.0362.

The Fitted regression line for Model UCS is

$$y = -0.933 + 0.120x_1 + 0.341x_2 + 0.136x_3 + 0.055x_4 - 0.237x_5 - 0.669x_6 + 0.194x_7 - 0.008x_8 + 2.763x_9 + 0.177x_{10}$$

The Fitted regression line for Model k is

$$y = 4.654 - 1.279x_1 - 0.156x_2 - 0.173x_3 - 0.004x_4 + 0.275x_5 + 0.184x_6 - 0.104x_7 - 0.027x_8 - 7.704x_9 + 1.140x_{10}$$

	Model UCS		**Model k**
y=	% UCS Increase	y=	% Permeability Decrease
x_1=	Type of Soil	x_1=	Type of Soil
x_2=	Conc. Of Anode	x_2=	Conc. Of Anode
x_3=	Conc. Of Cathode	x_3=	Conc. Of Cathode
x_4=	Voltage Applied	x_4=	Voltage Applied
x_5=	Current	x_5=	Current
x_6=	Current Density	x_6=	Current Density
x_7=	Ambient Temperature	x_7=	Ambient Temperature
x_8=	No. of days	x_8=	No. of days
x_9=	pH of Soil	x_9=	pH of Soil
x_{10}=	Permeability	x_{10}=	UCS

It is can be concluded that the injection of chemical solutions during electroosmosis is an effective method to enhance the effect of electroosmosis. Calcium chloride and sodium silicate solutions used as grouting materials due to their noticeable advantage of non toxicity and non contamination as well as being low cost can now be easily injected into clayey soils with the application of any hydraulic pressure thus negate the fear of hydraulic fracturing. The flow of grout increases with the increase in the applied voltage as well as reduction in the electrode spacing. The richer mix provides a higher improvement though this needs to be investigated for the grout mix to be flowable under atmospheric conditions.

8.2.3 Electrokinetic Dewatering using Conductive Geotextiles

- To obtain the variation in dewatering, the maximum water removal was observed in Soil 6 and minimum water removal was observed in Soil 1 with the corresponding maximum vane shear strength improvement of 147.20% obtained in case of Soil 6 (DM 5) and minimum of 60.15% noted in Soil 1(DM 1).
- Maximum water removal was observed in GWT 5 (Cotton Yarn & Steel filament in weft and warp) with higher improvement in vane shear strength of 169.23%, with a minimum value observed for GWT 1(Copper Wrapped Polyester Yarn) with lower vane shear strength of 23.10%.
- Conductive coating was varied with respect to the conductive nanoparticles formed and the coating based used, wherein maximum water removal was observed when using CNWG 2 (Poly (o-toluidine)/nylon 6) with a corresponding maximum improvement in vane shear strength of 405.20%, with CNWG 1 (Emeraldine base/ nylon 6) giving minimum water removal as well as minimal vane shear strength improvement of 322.11%.
- Rerun effect to verify the longevity of the coating on nonwoven geotextiles showed that the conductive coating formed using emeraldine base with polycarbonate, gave higher water removal and higher improvement in vane shear strength of 210.00%, though the conductive coating with poly o-toludine with nylon 6 was only a tad low with improvement in vane shear being of the order of 195.60%.
- A conductive geotextiles does not perform similarly for different compositions soils, which was studied with conduction of dewatering on two different soils with varying clay content wherein the lower clay content should higher water reduction and improvement in vane shear strength to the tune of 322.10%, wherein the soil with higher clay content showed lower reduction in water content and an improvement in vane shear strength of 199.49%.
- The conductive geotextile proved excellent when used as a vertical geodrain giving an improvement in the vane shear strength of the order of 686.52%.

It can be concluded that the woven geotextile proves better as opposed to coated conductive geotextile. The best woven geotextile proved to be cotton yarn with steel filament in both the warp and weft weaving whereas copper though being a good conductor does not provide a better option. The conductive geotextile also proves effective in all different types of soils under study.

8.3 CONTRIBUTION

- The successful removal of nickel from contaminated soil was performed.
- First successful application of a two component chemical grout (Sodium Silicate – Calcium chloride) was introduced using electrokinetic process without any pressure application.
- Concept of weaving of conductive geotextiles from routine material using handloom weaving.
- Concept of coating non woven geotextiles to form conductive coated geotextiles using nano-particles.
- New method of dewatering of soft soil using conductive woven and conductive coated nonwoven geotextiles as electrodes under DC field.

8.4 PRACTICAL CONSIDERATIONS

- Simultaneous application of both purging solutions, provides better efficiency of removal though the combination needs to be reviewed when any other heavy metal is under consideration.
- Preliminary test should be carried out in the field in order to confirm the applied voltage as well as its configuration.
- Use of a two component grout system in field needs to be verified for the type of soil under consideration.
- The grout system can be used to create physical barrier system to protect the further spread of the contaminant and for any future accidental spills or leachates form damaged landfill liners.
- The conductive geotextiles can be used to form vertical drains for easier removal of water thereby reducing the time for consolidation using conventional vertical geodrains.

8.5 FUTURE SCOPE OF RESEARCH

- With successful results for efficient remediation obtained in the present study in laboratory bench scale experiments, design of a pilot scale 3-dimensional test would be very desirable. This would also demonstrate the use of practical electrode materials.
- Further experiments considering real world material from the field, including multiple contaminant species, to provide a better understanding of the process.
- An important future research should be the study and evaluation of methods aimed at controlling the changes in the chemical environment due to electrodes reactions.

- Development of electrokinetics as a method not only to transport surfactants for remediation purpose but also to transport bacteria as remediation agents by electrophoretically transportation of the species.
- From a more geotechnical point of view, research to be focused on the control of hydraulic pressures inside the samples and on changes in the hydromechanical behavior of the soils when the pore fluid changes composition during the process.
- Research to be carried out on a more practical basis for the application of the processes, paying the special attention to the presence of natural particle size and mineralogical heterogeneities and on their influence of the fluxes when dealing with on-site problems.
- More effort is required to develop realistic numerical models for electrokinetic remediation. Any new approach should address important factors such as nonlinear electrical potential, pH dependent variation of conductivity, and the effect of coupled electrical-hydraulic gradients in ion transport, Also particular attention needs to be paid to the boundary conditions.
- Since a wide range of different experimental set-ups are used by different researchers, any attempt to standardize the electrokinetic apparatus would be beneficial in comparison of results.
- Besides the physical parameters that have been used in current regression and ANN models for prediction of heavy-metal removal from soil, the type of clay mineral can be studied to be included in the model, so as provide a more realistic results.
- Research for grouting, soil contaminated with inorganic and organic compounds might be carried out.
- Further testing of soft compressible soils should be performed to obtain effect of high voltage electrokinetic effects. This will enable a better understanding of the mechanisms involved in the strengthening of soils after high voltage application.
- An exanimation of any changes to the soi1 fabric or electrical properties of the clayey soils tested such as the possibility of an increase in the cementation bonds between soil particles and a change in the zeta potential.
- It is still unknown if an electrical current is generated in the soil due to leakage of the insulation, and if so, the magnitude of the "leakage current". A method of measuring current in the order of micro-amperes and measuring the actual potential distribution in the soil needs to be developed.
- Development and use of electrical resistivity as a tool for measurement of effectiveness of grouting is recommended.

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7. Electrokinetic Grouting for Stabilization of Copper Contaminated Soil – Second Indian Young Geotechnical Engineers Conference, Kakinada, 14th -15th March 2009. **(BEST PAPER AWARD)**
8. Effect of Contamination on Soil Properties and its Remediation – International Conference on Advances in Concrete, Structural and Geotechnical Engineering, BITS Pilani, 25-27 October 2009.
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13. Stabilization– Reutilization of Heavy Metal Contaminated Waste - National Seminar On Advances in Geotechnical Engineering, SVNIT, Surat 8th – 9th October 2011.
14. Strengthening Silty Soil using Electrokinetic Grouting - Indian Geotechnical Conference 2011, Kochi, 15th -17th December 2011.
15. Effect of Soil Type on Electrokinetic Dewatering of Soft Soils & Slurries using Conductive Textile - Indian Geotechnical Conference 2011, Kochi, 15th -17th December 2011.
16. Electrokinetic Dewatering Of Soil Using Multi-Filament and Spun Yarn Conductive Woven Fabrics - Indian Geotechnical Conference 2011, Kochi, 15th -17th December 2011. **IGS Z Tech Pvt. Ltd. Biannual Prize for Best Paper on "Geosynthetics & Allied Construction Products"**
17. Electrokinetic Grouting for Soft Soil Strengthening: Effect of model size, supply frequency, reactant type and its concentration – International Congress of Environmental Research, SVNIT, Surat, 15th -17th December 2011.
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INCOME TAX PAID............
ECOLOGICAL LAGAAN STILL UNPAID................

Well, we all know what tax or lagaan means.....

Throughout the history, tax or lagaan has always been an integral part of our lives. It has always been taken from every person who earns, buys or owns property and services. But names are different like land tax, income tax, sales tax & so on....

In the history of human civilization environment is always been superior in paying lagaan to use in the form of its rich & varied ecological heritage. But in tern what have we given back to our mighty earth?

Today, much of the world has progressed but still ecological lagaan remains unpaid. It is nothing but a path way to our rights over the use of natural resources. Unlike the film "Lagaan" when shall we repay the Environmental Lagaan and win the match in our real lives.