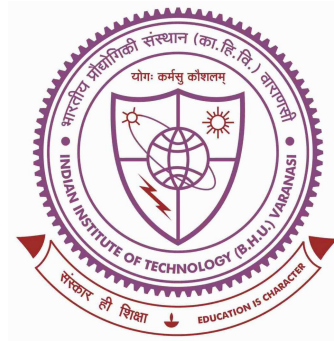


# Assessment of Alkali-Induced Heaving in Soil and its Stabilisation using Additives through Electrokinetics



Thesis submitted in partial fulfillment  
for the award of degree

Doctor of Philosophy

by

**Manish Kumar Mandal**

**DEPARTMENT OF CIVIL ENGINEERING**  
**Indian Institute of Technology**  
**(Banaras Hindu University)**  
**Varanasi**

Roll No: 15061009

2022



*Dedicated*  
*To*  
*My Beloved Family & Friends*



## CERTIFICATE

It is certified that the work contained in the thesis titled **Assessment of Alkali-Induced Heaving in Soil and its Stabilisation using Additives through Electrokinetics** by **Manish Kumar Mandal** has been carried out under my supervision and that this work has not been submitted elsewhere for a degree. It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy, and State of the Art (SOTA) for the award of Ph.D. Degree.

Dr. Bala Ramudu Paramkusam

(Supervisor)

Department of Civil Engineering  
Indian Institute of Technology  
(Banaras Hindu University)  
Varanasi, India - 221005



## DECLARATION

I, **Manish Kumar Mandal**, certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of **Dr. Bala Ramudu Paramkusam** from 21-July-2015 to 20-July-2022, at the Departement of Civil Engineering, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports, dissertations, thesis, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

Date:

Place: (Manish Kumar Mandal)

## CERTIFICATE BY THE SUPERVISOR

It is certified that the above statement made by the student is correct to the best of my/our knowledge.

**Dr. Bala Ramudu Paramkusam**  
supervisor

**Signature of Head of Department/Coordinator of School**  
”SEAL OF THE DEPARTMENT/SCHOOL”



# COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis: **Assessment of Alkali-Induced Heaving in Soil and its Stabilisation using Additives through Electrokinetics**

Name of Student: **Manish Kumar Mandal**

## Copyright Transfer

The undersigned hereby assigns to the Indian Institute of Technology (Banaras Hindu University), Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of the Doctor of Philosophy.

Date:

Place:

**(Manish Kumar Mandal)**

Note: However, the author may reproduce or authorize others to reproduce material extracted verbatim from the thesis or derivative of the thesis for author's personal use provided that the source and the Institute's copyright notice are indicated.



# Acknowledgments

First of all, I would want to begin by praising and thanking **Lord Shiva**, who has bestowed me with innumerable blessings, knowledge, and opportunities, allowing me to complete my thesis. Though, only my name appears on the cover of this dissertation, the success of this thesis rests heavily on the support and direction of many others. I owe my heartfelt gratitude to all those people who have made this thesis possible and because of whom my post graduate experience has been one that I will cherish forever.

I would like to take this opportunity to thank and appreciate my supervisor, **Dr. Bala Ramudu Paramkusam**, Civil Engineering Department, IIT(BHU), Varanasi, for his exceptional guidance, monitoring, and constant encouragement throughout the course of this dissertation. I would like to express my deepest appreciation to **Dr. Bala Ramudu Paramkusam** for his inspiration and helpful recommendations in completing my research work. I wish to extend my sincere gratitude towards my RPEC members, **Dr. Pabitra Ranjan Maiti** as an internal expert and **Prof. Rakesh Kumar Mishra** as an external expert, for their help, valuable suggestions, and encouragement during the entire research work. I am grateful to my brother, **Mr. Uttam Kumar**, and my friend, **Ms. Ankita Singh**, who provided me with technical, moral, and emotional support during my research program.

I would also like to thank **Prof. P.K.S. Dikshit**, Head, Department of Civil Engineering, Indian Institute of Technology (BHU), Varanasi, for providing all the facilities related to my research work. I wish to express my deep regards to, **Prof. Arun Prasad**, **Dr. Suresh Kumar**, **Dr. Supriya Mohanty**, and **Dr. Manash Chakraborty** for their unconditional support at every moment during the progress of my research. I also extend my heartfelt regards to all the faculty members of the Civil Engineering Department.

I am also grateful to our laboratory staff, **Mr. Basanta Prasad**, **Mr. Netra Pal**,

**Mr. Deepak Kumar, and Mr. Shankar Ram**, for the assistance extended by them from time to time during this research work. I would also like to thank **Mr. Sudhanshu Pal** for his constant assistance throughout my experimental work. I am grateful to all the office staff and authorities of the Department of Civil Engineering, for their kind help during the period of my stay to complete the thesis work. I would also like to extend my sincere thanks to **Dr. Dhirendra Pal**, of Precision Instruments, for his innovative ideas and guidance throughout the work. I would also like to thank to the Hindalco Industries Limited, Renukoot, India for providing the photograph of contaminated sites.

I am thankful to my fellow friends **Mr. Rajesh Ranjan, Mrs. Deep Jyoti Singh, Mrs. Rashmi Shrivastava, Ms. Parul Rawat, Mr. Amit Kumar Ram, Mr. Surya Prasad, Mr. Saurav Sarkar, Mr. Abhay Kumar, Mr. Amit Singh, Mr. Punit Paurush and Mr. Gaurav Verma** for the thought-provoking discussions, their support, cooperation and sincere help in many ways.

In particular, a very special gratitude goes out to some special persons, with special mention to **Ms. Anjali, Mr. Bablesh Kumar Jha, Mr. Rahul Singh, Mr. Hari Mohan Singh, Mr. Madhu Babu, Mr. Shiwansu Shekhar, Mr. Sujeet Kumar, Mr. Abhishek Kumar, Mr. Satyajeet Mondal, Mr. Nitesh Gupta, and Mr. Jayvant Chowdahary** for their constant encouragement, love and moral support.

It gives me great pleasure to share the credit for my research work with all of my teachers who have taught me at various stages of my academic career.

Last but not least, I will be eternally grateful to my entire family for their faith, patience, encouragement, blessings, and love. I am grateful to my father, **Mr. Madhu Mandal**; mother, **Mrs. Punam Devi**; aunt, **Late. Sanjukta Devi**, and **Mrs. Asha Devi**, for motivating, believing in, and strengthening me to fly high. A special thanks to my special family for always holding my hand through the ups and downs.

Date: \_\_\_\_\_

Manish Kumar Mandal

# Contents

<b>List of Tables</b>	<b>xi</b>
<b>List of Figures</b>	<b>xiii</b>
<b>Preface</b>	<b>xxi</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Background . . . . .	1
1.2 Source of Alkali Contamination . . . . .	2
1.3 Field Incidents of Alkali Contamination . . . . .	3
1.4 Impact of Alkali Contamination . . . . .	5
1.5 Mitigation Techniques . . . . .	7
1.6 Motivation of Study . . . . .	8
1.7 Research Objectives . . . . .	9
1.8 Thesis Outline . . . . .	9
<b>2 Literature Review</b>	<b>11</b>
2.1 General . . . . .	11
2.2 Alkali-Induced Heaving . . . . .	11
2.3 Mineralogical Alterations in Alkali Interacted Soil . . . . .	13
2.4 Geotechnical Properties of Alkali Interacted Soil . . . . .	15
2.5 Heaving Suppression Technique . . . . .	16
2.5.1 Application of Salt Solutions . . . . .	16
2.5.2 Application of Waste Materials . . . . .	17
2.6 Soil Stabilisation Technique . . . . .	18
2.6.1 Mechanical Stabilisation . . . . .	19

2.6.2	Chemical Stabilisation . . . . .	20
2.6.2.1	Stabilisation using Ground Granulated Blast-Furnace Slag (GGBFS) . . . . .	21
2.6.2.2	Stabilization using Alccofine . . . . .	24
2.6.2.3	Stabilization using other Inorganic Chemicals . . . . .	27
2.7	Stabilization of Soil using Bio-Chemicals . . . . .	30
2.8	Electrokinetic (EK) Technique . . . . .	33
2.9	Summary . . . . .	51
<b>3</b>	<b>Materials and Methods</b>	<b>53</b>
3.1	General . . . . .	53
3.2	Material Selection . . . . .	53
3.2.1	Soil . . . . .	53
3.2.2	Geotechnical Tests . . . . .	54
3.2.2.1	Particle Size Distribution . . . . .	54
3.2.2.2	Atterberg Limits . . . . .	55
3.2.2.3	Specific Gravity . . . . .	55
3.2.2.4	Compaction Characteristics . . . . .	56
3.2.2.5	Unconfined Compressive Strength . . . . .	56
3.2.2.6	Triaxial Test . . . . .	57
3.2.3	Ground Granulated Blast-Furnace Slag (GGBFS) . . . . .	58
3.2.4	Alccofine . . . . .	59
3.2.5	Chemical Stabilizer . . . . .	61
3.2.5.1	Enzyme-Induced Carbonate Precipitation (EICP) . . . . .	61
3.2.5.2	Sodium Silicate . . . . .	62
3.2.5.3	Sodium Carbonate . . . . .	63
3.2.5.4	Calcium Chloride . . . . .	64
3.2.6	Alkali Solution . . . . .	64
3.2.7	Sample Preparation . . . . .	64
3.2.8	Mineralogical Studies . . . . .	65
3.2.9	Morphological Studies . . . . .	65
3.2.10	Electrokinetic Model Set-up . . . . .	66

3.2.10.1	Rectangular Model Tank Equipped with ElectroKinetics . . .	66
3.2.10.2	Circular Model Tank Equipped with ElectroKinetics . . . . .	67
3.2.10.3	Electrodes used in Large Scale Models . . . . .	69
3.2.10.4	Bench Scale ElectroKinetic Model . . . . .	72
3.2.10.5	Electrodes used in Bench Scale Model . . . . .	72
3.2.10.6	Voltage Sensors . . . . .	73
3.2.10.7	DC Supplier . . . . .	74
3.2.10.8	Motorized Stirrer . . . . .	74
3.3	Research Methodology Adopted . . . . .	74
3.4	Summary . . . . .	77
<b>4</b>	<b>Assessment of Alkali-Induced Heaving through Electrokinetics</b>	<b>79</b>
4.1	General . . . . .	79
4.2	Effect of Alkali Concentration on Soil . . . . .	80
4.2.1	Particle Size Analysis . . . . .	80
4.2.2	Atterberg Limits . . . . .	80
4.2.3	Specific Gravity . . . . .	81
4.2.4	Compaction Characteristics . . . . .	82
4.2.5	Heaving Analysis . . . . .	82
4.2.6	Heaving Pressure . . . . .	84
4.2.7	Unconfined Compressive Strength . . . . .	85
4.2.8	Shear Strength Parameters . . . . .	86
4.2.9	Zeta Potential . . . . .	86
4.2.10	Dielectric Constant . . . . .	87
4.2.11	X-ray fluorescence analysis . . . . .	87
4.2.12	Mineralogical Analysis . . . . .	89
4.2.13	Micro Structural Analysis . . . . .	90
4.3	Alkali-Induced Soil Heaving in Large Scale Model through Electrokinetics	91
4.3.1	Rectangular Model Equipped with Electrokinetics . . . . .	93
4.3.2	Circular Model Equipped with Electrokinetics . . . . .	93
4.3.3	Sample Preparation . . . . .	93
4.3.4	Electrokinetic Mechanism . . . . .	94

4.3.5	Comparison of Rectangular and Circular Model Equipped with EK	95
4.3.5.1	Surface Heaving	95
4.3.5.2	Heaving Pressure in Large Scale Models	98
4.3.5.3	Variation of Electric Potential	98
4.3.5.4	Variation of Temperature	100
4.3.5.5	Variation of EO Flow	101
4.3.5.6	Unconfined Compressive Strength	101
4.3.5.7	Shear Strength Parameters	104
4.4	Summary	107
<b>5</b>	<b>Stabilization using Industrial Waste Materials</b>	<b>109</b>
5.1	General	109
5.2	Specimen Preparation	110
5.3	Experimental Results and Discussion	111
5.3.1	Particle Size Analysis	112
5.3.2	Atterberg Limits	112
5.3.3	Specific Gravity	114
5.3.4	Compaction Characteristics	116
5.3.5	Heaving Analysis	120
5.3.6	Unconfined Compressive Strength	122
5.3.7	Shear Strength Parameters	126
5.3.8	Mineralogical Studies	130
5.3.9	Microstructural studies	131
5.4	Bench Scale Study through Electrokinetics	134
5.4.1	Alkali Interacted Soil	134
5.4.2	Model Chamber	134
5.4.3	Sample Preparation for Bench-Scale Model Study	134
5.4.4	Experimental Results of the Electrokinetic Bench-Scale Study	135
5.4.4.1	Variation in Voltage During EK Test	135
5.4.4.2	Variation in pH of Electrolytic Solution During EK Test	135
5.4.4.3	Variation in Electroosmotic Flow During EK Test	138
5.4.4.4	Unconfined Compressive Strength Studies	138

5.5	Summary . . . . .	140
<b>6</b>	<b>Chemical Stabilization using Bench Scale Model through Electrokinetics</b>	<b>143</b>
6.1	General . . . . .	143
6.2	Test Procedure and Conditions . . . . .	144
6.2.1	Test Procedure and Conditions . . . . .	144
6.2.2	Electrokinetic Mechanism and Procedure . . . . .	146
6.2.3	Quantification of Precipitated Calcite (Acid Leaching test) . . . . .	147
6.3	Monitoring of Data During EK Test . . . . .	148
6.3.1	Variation of pH of Electrolytes and Soil . . . . .	149
6.3.2	Variation in Electric Potential . . . . .	153
6.3.3	Variation in Electroosmotic Flow During EK Process . . . . .	157
6.4	Results of Geotechnical Testing After EK Treatment . . . . .	159
6.4.1	Variation of Atterberg Limits of Post EK Treated Soil . . . . .	159
6.4.2	Variation in Unconfined Compressive Strength of Alkali Interacted Soil after EK Treatment . . . . .	164
6.4.3	Variation in Shear Strength Parameters of Alkali Interacted Soil after EK Treatment . . . . .	168
6.4.4	Variation in Coefficient of Compression of Alkali Interacted Soil after EK Treatment . . . . .	173
6.4.5	Heaving Analysis on Soil Stabilised with Chemicals . . . . .	176
6.4.6	Effect of EK Treatment with Chemicals on Mineral Composition of Alkali Interacted Soil . . . . .	179
6.4.7	Microstructural Study of Alkali Interacted Soil after EK Treatment with Different Chemicals . . . . .	183
6.5	Summary . . . . .	185
<b>7</b>	<b>CONCLUSIONS AND FUTURE SCOPE</b>	<b>187</b>
7.1	Summary and Conclusion . . . . .	187
7.2	Limitations and Scope for Future Work . . . . .	191
7.2.1	Limitations . . . . .	191
7.2.2	Scope for Future Work . . . . .	191



# List of Tables

Table 2.1: Electrokinetic enhanced technique for rapid consolidation of low permeable soil. . . . .	36
Table 2.2: Removal of different pollutant form contaminated soil using EK technique. . . . .	45
Table 3.1: Physical properties and chemical compositions of GGBFS . . . . .	59
Table 3.2: Physical properties and chemical compositions of Alccofine . . . . .	60
Table 3.3: Test combinations of EICP for stabilizing alkali interacted soil . . . . .	62
Table 3.4: Test combinations of sodium silicate . . . . .	63
Table 3.5: Test combinations for sodium carbonate . . . . .	63
Table 3.6: Specification of voltage sensor . . . . .	74
Table 5.1: Summary of tests combinations with varying percentage of GGBFS and AF . . . . .	111
Table 6.1: Summary of different combinations of chemical used in EK tests . . . . .	145
Table 6.2: Variation in $\text{CaCO}_3$ with different combination of chemicals . . . . .	148



# List of Figures

Figure 1.1:	Production volume of alkali chemicals in India from financial year 2013 to 2021(Source, www.statista.com) . . . . .	3
Figure 1.2:	Consumption of different percentages (by volume) of NaOH solution in varying industries (source: CHEMANALYST) . . . . .	4
Figure 1.3:	Leakage of alkali solution during unloading in an aluminium plant	5
Figure 1.4:	Heaving in wall of railway platform of aluminium plant due to alkali interaction . . . . .	6
Figure 1.5:	Impact of alkali contamination on soil . . . . .	7
Figure 2.1:	Percentage swelling in red earth and ball clay after inundation with different concentrations of alkali solution (Chavali et al., 2017).	13
Figure 2.2:	Use of Fly ash and GGBFS for the suppression of alkali induced heaving (Vindula et al., 2018; Vindula et al., 2019) . . . . .	19
Figure 3.1:	Soil used in the study . . . . .	54
Figure 3.2:	Grain size distribution of soil . . . . .	55
Figure 3.3:	Compaction Curve of Soil . . . . .	57
Figure 3.4:	GGBFS used in this study . . . . .	58
Figure 3.5:	Alccofine used in this study . . . . .	60
Figure 3.6:	Interaction of alkali solution with soil (a) polythene bag (b) air drying of alkali interacted soil . . . . .	65
Figure 3.7:	Elevation view of the rectangular electrokinetic model . . . . .	67
Figure 3.8:	Plan view of the rectangular electrokinetic model . . . . .	67

Figure 3.9:	Rectangular EK model image (a) Soil chamber installed with dummy electrode (b) Soil chamber with dial gauge and proving ring . . . . .	68
Figure 3.10:	Elevation view of circular electrokinetic model . . . . .	68
Figure 3.11:	Plan View of Circular EK Model . . . . .	69
Figure 3.12:	Circular EK model (a) soil chamber (b) soil with dummy electrode	70
Figure 3.13:	Circular EK model soil with dial gauge and proving ring . . . . .	70
Figure 3.14:	Electrode used in this study made of (a) brass net wrapped in (b) geotextile (c) EKG electrode . . . . .	71
Figure 3.15:	DC Supplier for the application of voltage gradient . . . . .	72
Figure 3.16:	Schematic Diagram of bench scale electrokinetic model . . . . .	73
Figure 3.17:	Bench scale electrokinetic model . . . . .	73
Figure 3.18:	Image of (a) Electrode, (b) Voltage sensor, and (c) Motorized stirrer	75
Figure 3.19:	Flow chart showing methodology of the study . . . . .	76
Figure 4.1:	Particle size analysis of soil after alkali interaction . . . . .	80
Figure 4.2:	Atterberg limits of soil with NaOH solution . . . . .	81
Figure 4.3:	Specific Gravity of soil with alkali interaction . . . . .	82
Figure 4.4:	Compaction curve of soil with alkali interaction . . . . .	83
Figure 4.5:	Heaving in soil due to inundation of NaOH Solutions . . . . .	84
Figure 4.6:	Heaving Pressure in soil due to inundation of NaOH Solutions . .	85
Figure 4.7:	UCS value of alkali interacted soil . . . . .	86
Figure 4.8:	Variation in cohesion of soil with different molarities of NaOH solution . . . . .	87
Figure 4.9:	Variation in angle of internal friction of soil with different molarities of NaOH solution . . . . .	88
Figure 4.10:	Zeta potential of soil after alkali interaction . . . . .	88
Figure 4.11:	Dielectric Constant of soil after alkali interaction . . . . .	89
Figure 4.12:	X-ray Chemical Composition of different soil inundated with water and alkali . . . . .	90
Figure 4.13:	XRD analysis of uninteracted soil and alkali interacted soil with 16M NaOH solution . . . . .	91

Figure 4.14:	SEM images of (a), (b) uninteracted soil and (c), (d) alkali inter-acted soil . . . . .	92
Figure 4.15:	CPT test results for (a) rectangular model and (b) circular model	94
Figure 4.16:	Heaving in soil inundated with 16M NaOH solution in rectangular model . . . . .	95
Figure 4.17:	Heaving in soil inundated with 16M NaOH solution in circular model	96
Figure 4.18:	Effect of model boundaries on percentage heaving . . . . .	97
Figure 4.19:	Heaving pressure in soil due to alkali interaction in large scale models . . . . .	98
Figure 4.20:	Variation of electrical potential in rectangular model . . . . .	99
Figure 4.21:	Variation of electrical potential in circular model . . . . .	100
Figure 4.22:	Variation of temperature in rectangular model . . . . .	101
Figure 4.23:	Variation of temperature in circular model . . . . .	102
Figure 4.24:	Variation in discharge volume of electroosmotic flow in large scale model . . . . .	102
Figure 4.25:	Variation in UCS value of soil sample collected from circular model	103
Figure 4.26:	Variation in UCS value of soil sample collected from rectangular model . . . . .	103
Figure 4.27:	Variation in angle of internal friction and of soil sample collected from rectangular model . . . . .	104
Figure 4.28:	Variation in cohesion value of soil sample collected from rectangular model . . . . .	105
Figure 4.29:	Variation in angle of internal friction of soil sample collected from circular model . . . . .	106
Figure 4.30:	Variation in cohesion value of soil sample collected from circular model . . . . .	106
Figure 5.1:	Prepared sample in air tight polythene bag . . . . .	111
Figure 5.2:	Particle size analysis of uninteracted soil, alkali interacted soil, GGBFS and AF . . . . .	112
Figure 5.3:	Atterberg limit with GGBFS . . . . .	113
Figure 5.4:	Atterberg limit with AF . . . . .	113
Figure 5.5:	Specific gravity with GGBFS . . . . .	115

Figure 5.6:	Specific gravity with AF . . . . .	115
Figure 5.7:	Compaction characteristics of uninteracted soil with GGBFS . . .	117
Figure 5.8:	Compaction characteristics of alkali interacted soil with GGBFS .	118
Figure 5.9:	Compaction characteristics of alkali interacted soil with GGBFS .	118
Figure 5.10:	Compaction characteristics of soil with AF . . . . .	119
Figure 5.11:	Compaction characteristics of alkali interacted soil with AF . . .	119
Figure 5.12:	Variation of MDD and OMC with AF . . . . .	120
Figure 5.13:	Heave in soil inundated with 16 M sodium hydroxide solution and stabilises with different percentages of GGBFS . . . . .	121
Figure 5.14:	. Heave in soil inundated with 16 M sodium hydroxide solution and stabilises with different percentage of AF . . . . .	122
Figure 5.15:	Compressive strength of uninteracted soil after GGBFS treatment	123
Figure 5.16:	Compressive strength of alkali interacted soil after GGBFS treat- ment . . . . .	124
Figure 5.17:	. Compressive strength of uninteracted soil after AF treatment . .	124
Figure 5.18:	. Compressive strength of alkali interacted soil after AF treatment	125
Figure 5.19:	Variation in cohesion of US and AIS with 20% GGBFS . . . . .	126
Figure 5.20:	Variation in angle of internal friction of US and AIS with 20% GGBFS . . . . .	127
Figure 5.21:	Variation in cohesion of US and AIS with 20% AF . . . . .	128
Figure 5.22:	Variation in angle of internal friction of US and AIS with 20% AF	129
Figure 5.23:	XRD of uninteracted soil and interacted soil treated with 20% GGBFS . . . . .	131
Figure 5.24:	XRD of uninteracted soil and interacted soil treated with 20% AF	132
Figure 5.25:	SEM image of (a) Uniteracted soil, (b) alkali interacted soil, (c), (d) soil treated with 20% GGBFS, (e), (f) soil treated with 20% AF . . . . .	133
Figure 5.26:	Variation of voltage in bench-scale EK set-up with GGBFS . . . .	136
Figure 5.27:	Variation of voltage in bench-scale EK set-up with AF . . . . .	136
Figure 5.28:	Variation in pH of electrolytes during EK test with GGBFS . . .	137
Figure 5.29:	Variation in pH of electrolytes during EK test with AF . . . . .	137

Figure 5.30:	Variation in cumulative discharge with time in bench scale EK setup . . . . .	139
Figure 5.31:	Variation in Unconfined Compressive Strength of soil after GG-BFS treatment . . . . .	139
Figure 5.32:	Variation in Unconfined Compressive Strength of soil after AF treatment . . . . .	140
Figure 6.1:	Step-by-step procedure for acid leaching test . . . . .	148
Figure 6.2:	Variation of pH of anolyte and catholyte with EICP . . . . .	149
Figure 6.3:	Variation of pH of anolyte and catholyte with sodium carbonate .	150
Figure 6.4:	Variation of pH of anolyte and catholyte with sodium silicate .	151
Figure 6.5:	Variation in pH of soil at different locations treated with EICP .	152
Figure 6.6:	Variation in pH of soil at different locations treated with sodium carbonate . . . . .	152
Figure 6.7:	Variation in pH of soil at different locations treated with sodium silicate . . . . .	153
Figure 6.8:	Variation of voltage at different locations after EICP treatment .	154
Figure 6.9:	Variation of voltage at different locations after sodium carbonate treatment . . . . .	155
Figure 6.10:	Variation of voltage at different locations after sodium silicate treatment . . . . .	156
Figure 6.11:	Variation of electroosmotic flow with time (EICP) . . . . .	157
Figure 6.12:	Variation of electroosmotic flow with time (sodium carbonate) . .	158
Figure 6.13:	Variation of electroosmotic flow with time (sodium silicate) . . . .	158
Figure 6.14:	Flow diagram of sample extraction . . . . .	160
Figure 6.15:	Variation in Liquid Limit values for various test combinations of EICP . . . . .	160
Figure 6.16:	Variation in Plastic Limit values for various test combinations of sodium carbonate . . . . .	161
Figure 6.17:	Variation in Liquid Limit values for various test combinations of sodium carbonate . . . . .	162
Figure 6.18:	Variation in plastic Limit values for various test combinations of sodium carbonate . . . . .	162

Figure 6.19:	Variation in Liquid Limit values for various test combinations of sodium silicate . . . . .	163
Figure 6.20:	Variation in plastic Limit values for various test combinations of sodium silicate . . . . .	164
Figure 6.21:	Variation of UCS for different test combinations of EICP . . . . .	165
Figure 6.22:	Variation of UCS for different test combinations of Sodium carbonate . . . . .	166
Figure 6.23:	Variation of UCS for different test combinations of Sodium carbonate . . . . .	167
Figure 6.24:	Variation in cohesion of treated soil for different test combinations of EK-EICP . . . . .	168
Figure 6.25:	Variation in angle of internal friction of treated soil for different test combinations of EK-EICP . . . . .	169
Figure 6.26:	Variation in cohesion of treated soil for different test combinations of sodium carbonate . . . . .	169
Figure 6.27:	Variation in angle of internal friction of treated soil for different test combinations of sodium carbonate . . . . .	171
Figure 6.28:	Variation in cohesion of treated soil for different test combinations of sodium silicate . . . . .	172
Figure 6.29:	Variation in angle of internal friction of treated soil for different test combinations of sodium silicate . . . . .	172
Figure 6.30:	Variation in coefficient of compression along the specimen length treated with EICP . . . . .	173
Figure 6.31:	Variation of coefficient of compression along the specimen length treated with Sodium Carbonate . . . . .	174
Figure 6.32:	Variation of coefficient of compression along the specimen length treated with Sodium Silicate . . . . .	175
Figure 6.33:	Variation in percentage heaving with time in soil and EICP treated soil . . . . .	176
Figure 6.34:	Variation in percentage heaving with time in soil and Sodium Carbonate treated soil . . . . .	177

Figure 6.35: Variation in percentage heaving with time in soil and Sodium silicate treated soil . . . . .	178
Figure 6.36: XRD pattern of uninteracted soil, alkali interacted soil and EICP treated soil . . . . .	180
Figure 6.37: XRD pattern of uninteracted soil, alkali interacted soil and sodium carbonate treated soil . . . . .	181
Figure 6.38: XRD pattern of uninteracted soil, alkali interacted soil and sodium silicate treated soil . . . . .	182
Figure 6.39: SEM image of alkali interacted soil, (a), (b) treated with EICP, (c), (d) treated with sodium carbonate, and (e), (f) treated with sodium silicate . . . . .	184



# Preface

Sodium hydroxide is a valuable alkali that has been used in various industries including paper and pulp, soap and detergent, petroleum, textile, and alumina industries etc extensively. According to World Bureau of Metal Statistics, the production of aluminium has been doubled to approximately 3.55 million metric tonnes in the last decade which consumes large volume of sodium hydroxide manufactured. The huge production and utilisation of sodium hydroxide make it a causative source of sub-surface soil pollution in many parts of the world, particularly in locations where it is thriving. The intense interaction of chemical contamination causes mineralogical and microstructural changes in soil, resulting in alteration in the geotechnical properties of soil. Apart from this, one major problem associated with the alkali interaction is unexpected heaving in the foundation soil that causes failure of the structure. Therefore, it is pertinent to take into account the heaving behaviour and alteration in geotechnical properties of such contaminated sites as well as to find out the remedial measures to control alkali-induced-heaving and to improve the geotechnical properties of alkali-interacted soils. With the aim of assessing these problems, an attempt has been made to evaluate the heaving and other geotechnical behaviour of soil by prolonged interaction of different concentrations of alkali contaminant and also to develop remedial measures to control the alkali-induced heaving and to suppress the detrimental effect of alkali on the soil. Despite that, a sustainable and dependable remediation strategy can be proposed to perform in-situ to counteract the deteriorating effect of alkali contamination on the strength of the soil.

A comprehensive experimental programme has been planned to achieve these objectives. The experimental investigations along with the detailed material methodology and the results obtained are discussed into seven chapters of this thesis. The first chapter provides a background of the effect and source of alkali contamination, along with some case histories of structural failure due to alkali contamination and the need for its consideration

from a geotechnical point of view. The second chapter summarizes a detailed review of the documented literature on the effect of alkali contamination on heaving as well as deterioration of geotechnical properties of soil and the use of different additives to control the alkali-induced heaving and to improve the geotechnical properties of alkali-contaminated soil. The application of the electrokinetic (EK) technique for the stabilisation of problematic soil is also presented in detail in this chapter. The different materials used and various methodologies adopted in the study are presented in detail in chapter 3. The soil used in the study was collected within the campus of Banaras Hindu University, Varanasi, which was later artificially contaminated with NaOH at concentrations of 8, 12, and 16 M in the laboratory. Followed by the selection of industrial waste by-products and different chemicals to control the alkali-induced heaving as well as for stabilising of alkali-interacted soil. The chapter also gives a detailed design and fabrication of the large-scale rectangular, circular and bench scale EK equipped models used in this dissertation.

The fourth chapter presents a series of geotechnical tests conducted for an assessment of the effects of different concentrations of alkali solution on the heaving behaviour and alterations in the engineering properties of the soil. Later, the 16 M NaOH solution was used to assess the alkali-induced heaving in the large-scale rectangular and circular models through the electrokinetic technique. The fifth chapter presents a series of geotechnical tests to investigate the influence of different percentages of two different industrial waste by-products namely, Ground Granulated Blast Furnace Slag (GGBFS) and Alccofine, on the alkali-induced heaving and their efficiency to improve the engineering properties of uninteracted soil and alkali interacted soil. Further, the optimum percentage of waste by-products was used to stabilize the alkali interacted soil through a bench scale EK model to simulate the field condition. The sixth chapter aims to examine the effect of different three concentrations of three chemical stabilizers (Enzymatic Induced Calcite Precipitate (EICP), sodium silicate and sodium carbonate with calcium chloride salts) on the index and strength properties of alkali interacted soil through bench scale electrokinetic test. The test results show that the addition of industrial waste by-product and the ingestion of chemicals not only enhanced the engineering properties of uninterated and alkali interacted soil but also controlled the alkali-induced heaving in soil effectively. The last chapter summarizes the major conclusions of the study along with its limitations and future recommendations. On one hand it was seen that alkali contamination significantly

deteriorates the engineering properties of the soil, on the other hand, a remarkable recovery was observed in those properties when stabilized through various industrial and chemical stabilizers. Although the large scale and bench scale studies have been attempted in this work, still there has been vast scope to further conduct these studies on a field scale for better reliability of the results.