



UNIVERSITI PUTRA MALAYSIA

***GYPSEOUS SOIL STABILIZATION BY ALKALINE ACTIVATION
METHOD***

SHAYMAA SADEQ KADHIM

FK 2017 50



**GYPSEOUS SOIL STABILIZATION BY ALKALINE ACTIVATION
METHOD**

By

SHAYMAA SADEQ KADHIM

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,
in Fulfillment of the Requirements for the Degree of Doctor of Philosophy**

March 2017

COPYRIGHT

All materials contained within this thesis including without limitation text, logos, icons, photographs and all other artwork, is copyright material of universiti putra mamysia unless otherwise stated. Use may be made of any material contained within the thesis for non – commercial purposes from copyright holder. Commercial use of material may only be made with the express, prior, written permission of Universiti Putra Malaysia

Copyright © Universiti Putra Malaysia



DEDICATION

This thesis is dedicated to Allah, my husband, my parents, and my children.



© COPYRIGHT UPM

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

GYPSEOUS SOIL STABILIZATION BY ALKALINE ACTIVATION METHOD

By

SHAYMAA SADEQ KADHIM

March 2017

Chairman : Professor Bujang Kim Huat, PhD
Faculty : Engineering

Gypseous soils cover a large area in Iraq and other parts of the world. In general, these soils are problematic and very sensitive to the moisture content or any wet conditions. In fact, water is able to dissolve the gypsum/salt in the soil and consequently the soluble particles are leached out, causing huge changes in the volume and geotechnical properties of the soil mass. Although cement and lime can improve some engineering properties of gypseous soils, they have several shortcomings, especially when viewed from an environmental perspective (e.g. carbon dioxide emissions). Moreover, when gypseous soil is treated with the calcium-based materials (i.e. cement/lime), the stabilized soil has low durability due to the formation of ettringite, especially when the soil has a high amount of gypsum. Therefore, it is significant to investigate a proper method to stabilize gypseous soil. Alkali-activated binders were used as a new method of soil stabilization in this study. Due to the energy efficiency, the environmental friendly nature of the process, and the excellent resulting engineering properties, alkali-activated binders are fast emerging as materials of choice for soil stabilization.

In this research, soil was collected from Babylon in Iraq. Different types of gypseous soils with different gypsum contents were prepared in order to identify the role of gypsum content in the soil. Fly ash class F was used as a precursor along with two types of activators at different molarities. Mechanical tests including compressive strength and mass loss and microstructural tests including XRD, BET, SEM, EDX, and TGA were performed on mortar before and after treatment and the effect of sulfate attack were investigated in the process. Gypseous soils were then treated with different alkaline activators for different curing times. Afterwards, UCS tests and collapsibility tests using the hydraulic Rowe cell system were performed to assess the effect of the treatment. Microstructural analyses were also performed to investigate the underlying mechanism. Finally, undrained triaxial tests were carried out to investigate the mechanical behaviour of the treated soils.

This research also includes an attempt to find an empirical correlation to predict the collapse index based on soil properties using the results of collapsibility tests.

The results showed that the alkaline activation method could stabilize the soils effectively. The collapse index decreased, and the mechanical performance of the treated soils improved. The microstructural analyses confirmed the durability of the stabilized mass. The study was important as it confirmed that the alkaline activation method played a dramatic role in the improvement of gypseous soil.

In addition, series of Rowe cell and shear strength tests are performed on these three models of collapsible soils under various conditions. The results indicate that the most important parameters affecting soil collapsibility are; fine percent, initial dry unit weight, prewetting pressure and water content. Collapse potential decreases with the increase in initial dry unit weight and water content. It is found that only a relatively small fine percentage is required to yield significant collapse, and collapse potential increases with pressure at wetting and fine particles increase. Rate of increase in the collapse potential decreases as fine particles percentage increases. In un-soaked samples with 13% gypsum (G13), while for 25% gypsum content (G25), the collapse potential was 7.95 (moderately severe), and finally for the high gypsum content of 45% (G45), the collapse potential increased to 10.75 and was rated as severe. As can be seen that a large reduction in collapse potential was recorded with a high concentration of activator. For instance, the collapse potential of gypseous soil with 45% gypsum activated with 30% fly ash activated with 8-M KOH was 8.69%, but when the molarity of the activator was increased to 12 M under the same condition, the collapse potential decreased to 3.7% after 7 days of curing.

On the other hand, the increase in the fly ash content from 10 to 30% reduced the collapse potential at different rates. As can be seen, the collapse potential for the soil with 45% gypsum content was 10.75 and decreased to 8.69, 5.88, and 3.7 in 12-M KOH samples and to 9.09, 6.64, and 4.48 in NaOH samples at 7 days when 10, 20, and 30% geopolymer fly ash was used to stabilize the gypseous soil.

The result of UCS for the gypseous soil with 45% gypsum content treated with fly ash activated with 12-M KOH. It can be observed that the compressive strength of the untreated gypseous soil was 0.531 Mpa and it was increased after treatment with fly ash geopolymerized with 12-M KOH; the addition of 30% activated fly ash led to a significant enhancement, giving a compressive strength of 2.216 MPa with a strain 4.668 after 7 days of curing.

Two collapse-predictive mathematical models are proposed by using the results of 165 Rowe cell tests. These models are of high and acceptable correlation factor of ($r^2=0.875$ and 0.87) and verified by experimental data.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

PENSTABILAN TANAH BERGIPSUM OLEH KAEDAH PENGAKTIFAN ALKALI

Oleh

SHAYMAA SADEQ KADHIM

Mac 2017

Pengerusi : Profesor Bujang Kim Huat, PhD
Fakulti : Kejuruteraan

Tanah bergypsum meliputi kawasan yang luas di Iraq serta kawasan-kawasan lain di dunia. Secara umum, tanah ini bermasalah dan sangat sensitif pada kandungan lembapan atau keadaan basah. Sebenarnya, air mampu melarutkan gipsum / garam di dalam tanah dan seterusnya zarah larut terlarut lesap, menyebabkan perubahan yang besar pada isipadu dan sifat geoteknikal jisim tanah. Walaupun simen dan kapur boleh meningkatkan beberapa ciri kejuruteraan tanah bergypsum, namun ia mempunyai beberapa kelemahan terutamanya apabila dilihat daripada perspektif alam sekitar (misalnya, pelepasan karbon dioksida). Tambahan pula, apabila tanah bergypsum dirawat dengan bahan-bahan berasaskan kalsium (iaitu simen / kapur), tanah yang distabilkan ini mempunyai ketahanan yang rendah kerana pembentukan *ettringite*, terutamanya jika tanah mempunyai jumlah gipsum yang tinggi. Oleh itu, kajian tentang kaedah yang betul bagi menstabilkan tanah bergypsum adalah penting. Dalam kajian ini pengikat yang diaktifkan oleh alkali digunakan sebagai satu kaedah baru dalam menstabilkan tanah. Kerana kecekapan tenaga, sifat proses yang mesra alam, serta dapat menghasilkan sifat kejuruteraan yang baik, pengikat yang diaktifkan oleh alkali semakin pesat digunakan sebagai bahan pilihan bagi menstabilkan tanah.

Dalam kajian ini, tanah telah diambil dari Babylon di Iraq. Tanah bergypsum yang berlainan jenis dengan kandungan gipsum yang berlainan telah disediakan untuk mengenal pasti peranan kandungan gipsum di dalam tanah. Abu terbang kelas F telah digunakan sebagai pelopor bersama-sama dengan dua jenis pengaktif pada kemolaran yang berbeza-beza. Ujian mekanikal termasuk kekuatan mampatan dan kehilangan jisim serta ujian mikrostruktur termasuk XRD, BET, SEM, EDX, dan TGA telah dilakukan pada mortar sebelum serta selepas rawatan dan seterusnya kesan serangan sulfat disiasat. Tanah bergypsum kemudiannya dirawat dengan pengaktif alkali yang berbeza-beza bagi masa pengawetan yang berbeza-beza. Kemudian, ujian UCS dan ujian boleh runtuh menggunakan sistem sel hidraulik Rowe telah dijalankan untuk menilai kesan rawatan. Analisis mikrostruktur juga dilakukan untuk menyiasat

mekanisme dalamannya. Akhir sekali, ujian tiga paksi tak bersalir telah dijalankan untuk menyiasat perlakuan mekanikal tanah yang dirawat. Kajian ini juga melibatkan usaha untuk mencari korelasi empirik bagi meramal indeks keruntuhan berdasarkan sifat-sifat tanah menggunakan keputusan ujian boleh runtuh. Hasil kajian menunjukkan kaedah pengaktifan alkali dapat menstabilkan tanah dengan berkesan. Indeks keruntuhan menurun dan prestasi mekanikal tanah yang dirawat meningkat. Analisis mikrostruktur mengesahkan ketahanan jisim yang distabilkan. Kajian ini penting kerana ia mengesahkan bahawa kaedah pengaktifan alkali memainkan peranan yang luar biasa dalam pembaikan tanah bergipsum.



ACKNOWLEDGEMENTS

First of all, my utmost gratitude goes to Allah.

Special appreciation and gratitude are extended to my supervisors **Bujang Kim Huat, PhD**, and **Prof. Dr Thamer Ahmed Mohamed** and to **Dr Afshin Asadi, PhD** for their encouragement, patience, supervision, guidance, and support from the initial to the final stage and completion of this thesis.

I would also like to thank **Dr Nima Farzadnia** and **Dr Moslih Amer** for his help during this work.

I would like to thank the Iraqi Ministry of Higher Education and Scientific Research for providing a scholarship. Moreover, I would like to thank all the staff of Universiti Putra Malaysia who supported me during the research process as well as the electric station of Kapar Energy, Selangor for providing the raw fly ash for use in this research.

I would like to express my heartfelt gratitude, indebtedness, and deep sense of respect to my husband Ali, my children, Zain, Baqir, and Jawad, my parents, Sadeq and my mother soul Samyrrah, my brothers, Ihasan and Haider, and my sister, Liqa.

Last but not least, I would also like to acknowledge all my friends and colleagues for their valuable encouragement, support, and help.

I certify that a Thesis Examination Committee has met on 29 March 2017 to conduct the final examination of Shaymaa Sadeq Kadhim on her thesis entitled "Gypseous Soil Stabilization by Alkaline Activation Method" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Abdul Halim bin Ghazali, PhD

Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Dato Mohd Saleh bin Jaafar, PhD

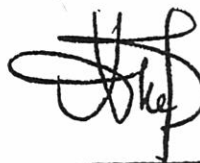
Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Mohd Raihan Taha, PhD

Professor
Universiti Kebangsaan Malaysia
Malaysia
(External Examiner)

Devendra Narain Singh, PhD

Professor
Indian Institute of Technology Bombay
India
(External Examiner)



NOR AINI AB. SHUKOR, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 6 July 2017

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Bujang Kim Huat, PhD

Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Thamer Ahmed Mohamed, PhD

Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Afshin Asadi, PhD

Research Fellow
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ROBIAH BINTI YUNUS, PhD

Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software

Signature: _____ Date: _____

Name and Matric No.: Shaymaa Sadeq Kadhim , GS38328

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

Signature: _____
Name of Chairman
of Supervisory
Committee: Professor Dr. Bujang Kim Huat

Signature: _____
Name of Member
of Supervisory
Committee: Professor Dr. Thamer Ahmed Mohamed

Signature: _____
Name of Member
of Supervisory
Committee: Dr. Afshin Asadi

TABLE OF CONTENTS

	Page
ABSTRACT	i
ABSTRAK	iii
ACKNOWLEDGEMENTS	v
APPROVAL	vi
DECLARATION	viii
LIST OF TABLES	xiii
LIST OF FIGURE	xiv
LIST OF ABBREVIATIONS	xviii
 CHAPTER	
1 INTRODUCTION	1
1.1 Background	1
1.2 Problem Statement	2
1.3 Aim of the Research	3
1.4 Objectives of the Research	4
1.5 Scope of the Research	4
1.6 Significance of the Research	5
1.7 Thesis Organization	5
 2 LITERATURE REVIEW	 7
2.1 Introduction	7
2.2 Gypseous Soil	7
2.2.1 Gypseous soil classification	8
2.3 Gypsum Mineral	8
2.3.1 Formation of Gypsum	8
2.3.2 Gypsum characteristics	10
2.3.2.1 Cementitious effect of gypsum	11
2.3.2.2 Solubility and rate of solution	12
2.3.3 Effect of gypsum on the engineering properties of gypseous soil	14
2.3.3.1 Water content, Atterberg limits and grain size distributions	14
2.3.3.2 Density and specific gravity	15
2.3.3.3 Compaction characteristics	15
2.3.3.4 Compressibility	16
2.3.3.5 Unconfined compressive strength (UCS)	19
2.3.3.6 Shear strength (triaxial)	20
2.3.3.7 Collapsibility	24
2.3.3.8 Permeability	26
2.4 The Collapse Mechanism of Gypseous Soil	27
2.4.1 Identification and measurement of soil collapsibility	30
2.4.2 Methods based on void ratio relationships	32
2.4.3 Methods based on moisture content and Atterberg limit relationships	34
2.4.4 Comparison with Previous Collapse-Prediction Model	35

2.5	Problems of Gypseous Soils	36
2.6	The Gypseous Soil Distribution	37
2.6.1	Regional distribution of gypseous soil in the world	38
2.6.2	Gypseous soil in Iraq	39
2.7	Gypseous Soil Improvement	41
2.7.1	The physical treatment	41
2.7.2	Chemical treatment	42
2.7.2.1	Cement treatment	45
2.7.2.2	Lime treatment	45
2.8	Geopolymer	46
2.8.1	Soil stabilization with geopolymer	50
2.9	Critical discussion	52
3	THE MATERIALS' PROPERTIES AND THE EXPERIMENTAL PROGRAMME	53
3.1	Introduction	53
3.2	Testing program	55
3.2.1	Soil testing	55
3.2.1.1	Natural gypseous soil	55
3.2.1.2	Index properties tests	56
3.2.1.3	Chemical tests	57
3.2.1.4	Determination of gypsum content	57
3.2.1.5	Compaction tests	58
3.2.2	Fly ash	58
3.2.3	Ordinary Portland Cement OPC and Sulfate Resistance Cement SR	59
3.2.4	KOH and NaOH	59
3.2.5	Sample Preparation	59
3.2.5.1	Mortar sampling	59
3.2.5.2	Soil sample preparation	61
3.3	Test Procedure	62
3.3.1	Sulfate attack on pure binder (mortar samples)	62
3.3.2	Mechanical and microstructural analysis tests for mortar	63
3.3.3	Compressive strength and mass loss	63
3.3.4	BET	64
3.3.5	Geotechnical tests of soil samples	65
3.3.6	Collapsibility test	65
3.3.7	Permeability and leaching tests (Rowe cell)	66
3.3.8	Unconfined compressive strength (UCS)	68
3.3.9	Triaxial test	68
3.3.10	Consolidated drained triaxial test	68
3.3.11	Consolidated undrained triaxial test	69
3.3.12	Microstructural tests of soil and mortar samples	70
3.3.13	Thermo-gravimetric analysis (TGA)	70
3.3.14	X-ray diffraction (XRD)	71
3.3.15	SEM and EDX tests	72
3.4	Computer program	72
3.4.1	Computer language	73
3.4.2	Computer program work	73

3.4.3	Statistical analysis (evaluation of the collected data)	74
4	ANALYSIS AND DISCUSSION OF THE RESULTS	75
4.1	General	75
4.2	Materials characterization	75
4.2.1	Natural soil characterization	75
4.2.2	Fly ash, OPC and SR characterization	78
4.3	Stabilization Part	79
4.3.1	Binder part (unsoaked)	79
4.3.1.1	Compressive strength results	79
4.3.1.2	XRD results	81
4.3.1.3	EDX results	83
4.3.1.4	SEM results	84
4.3.1.5	BET results	85
4.3.2	Binder part (soaked)	86
4.3.2.1	Compressive strength	86
4.3.2.2	Mass loss	89
4.3.2.3	XRD results	91
4.3.2.4	TGA results	97
4.3.2.5	EDX results	99
4.3.2.6	SEM results	102
4.3.2.7	BET results	104
4.4	Stabilized gypseous soil part	106
4.4.1	Stabilized gypseous soil (unsoaked)	106
4.4.1.1	Collapse potential	106
4.4.1.2	SEM results	109
4.4.1.3	EDX results	110
4.4.1.4	Permeability–Leaching	111
4.4.1.5	Unconfined compressive strength (UCS)	115
4.4.2	Stabilized gypseous soil (soaked)	117
4.4.2.1	Collapse potential	117
4.4.2.2	XRD Results	120
4.4.2.3	EDX Results	122
4.4.2.4	SEM results	124
4.4.2.5	Permeability–leaching	125
4.4.2.6	Unconfined compressive strength (UCS)	129
4.4.2.7	Undrained triaxial compression	132
4.4.2.8	Drained triaxial compression	133
4.5	Collapse Potential Predictive Model	134
4.6	Validity of the Proposed Collapse Predictive Model	135
5	CONCLUSIONS AND RECOMMENDATIONS	136
5.1	Conclusions	136
5.2	Recommendations for future researches	137
	REFERENCES	138
	APPENDICES	143
	BIODATA OF STUDENT	156

LIST OF TABLES

Table		Page
2.1	Gypseous soil classification (Barazanji, 1973)	8
2.2	Chemical compounds of gypsum and anhydrate, after Al-Muftly (1997a)	11
2.3	Average analysis of high grade gypsum	11
2.4	Compaction characteristics of gypseous soil	16
2.5	Variation of hydraulic conductivity (k) with gypsum content (as cited by Alphen and Romero 1971)	26
2.6	Reported criteria for identification of collapsing soil (after Das, 1990)	30
2.7	The severity of collapse potential (after Clemence and Finbarr 1981)	34
2.8	Reported equations for prediction of collapse potential	36
2.9	Elements of gypseous soil estimated around the world in line with the Harmonized World Soil Database (HWSD)	39
2.10	Physical treatment of gypseous soil	42
2.11	Chemical treatment of gypseous soil	43
2.12	Summary of researches performed on pozzolanic materials for soil improvement	49
2.13	Historical data in alkaline activation process	51
3.1	Mortar preparation mixture	60
3.2	Soil stabilization preparation mixture	62
4.1	Results of the physical and classification testing	75
4.2	The chemical components of the soil from the XRF test	76
4.3	Results of the chemical testing of gypseous soil	76
4.4	Chemical composition of fly ash	78

LIST OF FIGURES

Figure		Page
2.1	Cementation of soil grains: (1) soil grains, (2) cementing material, and (3) porosity (after Harwood, 1988)	12
2.2	Solution of a solid controlled by diffusion (after James and Kirkpatrick, 1980)	14
2.3	Mohr-Coulomb failure envelope for obtaining the limiting soil shear strength parameters (Bowles, 1979)	20
2.4	Variation in shear strength variables with gypsum content intended for gypseous soil sandy silt soil (after Petrukhin and Arakelyan, 1985)	24
2.5	The mechanism of collapse of grain structure upon wetting of the loaded soil: (a) before inundation and (b) after inundation (after Jennings and Knight, 1957)	28
2.6	Contact pressure produced by capillary (after Dudley, 1970)	29
2.7	Typical collapsible soil mechanisms, which hold loose, bulky grains in place (after Burden et al., 1973)	30
2.8	Double consolidometer test showing the effect of loading and wetting of collapsible soil (after Jennings and Knight, 1957)	33
2.9	Nature of variation of void ratio with pressure for a collapsing soil (after Das 1990).	34
2.10	Criteria for evaluating looseness and probability of soil collapse (after Gibbs, 1962)	35
2.11	Distribution of gypseous soils in the world (after FAO, 1990)	39
2.12	Distribution of gypseous soils in the world (after FAO, 1990)	40
3.1	Flow chart of the main research	54
3.2	Sampling location for the research	55
3.3	Atterberg limit test	56
3.4	Specific gravity test	57
3.5	Gypseous soil after oven drying	58

3.6	Activator liquid preparation stages	59
3.7	Mortar samples preparation	61
3.8	Soil sample preparation	62
3.9	Soaking stage for the mortar samples	63
3.10	Compressive strength device	64
3.11	BET device for the porosity test	65
3.12	Details of Rowe cell consolidation test: (a) schematic diagram of Rowe cell (Lee <i>et al.</i> 1983), (b) Rowe cell test set up (Duraismy <i>et al.</i> 2007), (c) Rowe cell device	66
3.13	Unconfined compression device	68
3.14	Triaxial test device	70
3.15	XRD device	71
3.16	SEM and EDX device	72
4.1	X-ray diffraction pattern of natural soil	76
4.2	Soil particles distribution	77
4.3	Moisture–density relation (standard compaction)	77
4.4	Moisture–density relations (modified compaction)	78
4.5	XRD graph of the fly ash	79
4.6	SEM image of the raw fly ash	79
4.7	Compressive strength of samples at 28 days.	80
4.8	XRD pattern of (a) raw fly ash, (b) 12-M KOH activated fly ash, and (c) 12-M NaOH activated fly ash	83
4.9	EDX point mapping of fly ash activated with (a) 12-M NaOH and (b) 12-M KOH	84
4.10	SEM images of (a) raw fly ash, (b) fly ash activated with 12-M KOH, (c) fly ash activated with 12-M NaOH	85
4.11	BET pattern of pore size distribution of fly ash activated with 12-M KOH and 12-M NaOH	86

4.12	Compressive strength of samples after 7, 28, and 90 days of exposure to (a) MgSO ₄ and (b) Na ₂ SO ₄	87
4.13	Relative losses in compressive strength of samples after 7, 28, and 90 days of exposure to (a) MgSO ₄ and (b) Na ₂ SO ₄	88
4.14	Weight loss (%) of samples after 7, 28, and 90 days of exposure to (a) MgSO ₄ and (b) Na ₂ SO ₄	91
4.15	XRD patterns of samples after 28 and 90 days of exposure	96
4.16	TGA spectra of unsoaked samples after 28 days and samples after 28 and 90 days of exposure: (a) unexposed samples, (b) samples exposed to MgSO ₄ , c) samples exposed to Na ₂ SO ₄	99
4.17	EDX of mortar samples after 28–90 days of soaking	102
4.18	SEM images of mortar samples after 28–90 days of soaking	104
4.19	The BET pattern of pore size distribution of mortar samples after 28–90 days of soaking	106
4.20	The unsoaked soil samples after 7, 28, and 90 days	109
4.21	SEM test for stabilized soil	110
4.22	EDX test for stabilized soil	111
4.23	Permeability test for stabilized soil before soaking	112
4.24	Leaching test for stabilized soil before soaking	115
4.25	UCS test for stabilized soil before soaking	117
4.26	Soaked soil samples after 7, 28, and 90 days	120
4.27	XRD graph showing the effect of soaking on stabilized soil samples	122
4.28	EDX test for stabilized soil after soaking	123
4.29	SEM test for stabilized soil after soaking	125
4.30	Permeability test for stabilized soil after soaking	127
4.31	Leaching test for stabilized soil after soaking	129
4.32	The UCS test results for stabilized soil after soaking	131
4.33	Unconfined compressive strength test of 45%G at 28 days	131

4.34	Undrained shear behaviour of a) untreated and b) treated gypseous soil at confining pressures of 40, 80, and 160 kPa	133
4.35	Drained shear behaviour of a) untreated and b) treated gypseous soil at confining pressures of 40, 80, and 160 kPa	134
4.36	Predicted values of collapse potential from Equation 4.1 vs. the tested values	135



LIST OF ABBREVIATIONS

G	Gypseous soil
G13%	Gypseous soil with 13% gypsum
G25%	Gypseous soil with 25% gypsum
G45%	Gypseous soil with 45% gypsum
F.A	Fly ash
KOH	Potassium hydroxide
NaOH	Sodium hydroxide
C-S-H	Calcium silicate hydrate
A-S-H	Aluminium silicate hydrate
N-A-S-H	Sodium aluminium silicate hydrate
GGBS	Ground granulated blast furnace slag
UCS	Unconfined compression test
MDD	Maximum dry density
OMC	Optimum moisture content
LL	Liquid limit
PL	Plastic limit
PI	Plastic index
XRD	X-ray diffraction
XRF	X-ray fluorescence
SEM	Scanning electron microscopy
EDX	Energy-dispersive X-ray spectroscopy
TGA	Thermogravimetric analysis
BET	Brunauer–Emmett–Teller surface area analysis
C _p	Collapse potential

K	Coefficient of permeability
OPC	Ordinary Portland cement
S.R	Sulfate-resistant cement
MgSO ₄	Magnesium sulfate
Na ₂ SO ₄	Sodium sulfate



CHAPTER ONE

INTRODUCTION

1.1 Background

In general, one of the most common means of stabilizing gypseous soil is by chemical treatment using cement or lime as an additive to the soil. Gypseous soils are considered as an issue and a riddle, which is the reason why these soils merit consideration. Gypseous soils (with light, moderate, or high gypsum contents) cover several parts of populated areas, especially in arid and semi-arid regions such as the Arabians peninsula, Russia, Armenia, the United States and Spain (Fattah, Al-ani, and Al-lamy 2013). The gypsum content is not only able to restrict water and dissolve in water but can also cause degradation impacts on concrete, metal, and building materials. In spite of that, understanding of the genesis and engineering properties of gypseous soils is essential and can be advanced by conducting research and tests on aspects including the formation process and the reaction of these soils from the construction side. The availability of gypsum in soil influences the soil improvement properties therefore several tests was done to determine the effects of treatment on chemical and engineering properties of gypseous soil and the effects of the soil environment.

The term “gypseous soil” is used for soils that contain gypsum. When gypseous soils are in the dry state, they tend to be stable and more cohesive than they are in wet conditions due to the behaviour of the cementation agent (gypsum) between the soil particles and the water. In other words, there is a great decrease in strength of the soil with an immediate increase in compressibility, especially when the soil is wet or leaching as a result of the dissolution of the gypsum (cementitious agent), so the bonds between the soil particles break down (Nashat, 1990). Gypseous soils are viewed as collapsible soils. In this manner, they are typically thought to be a hazard and they display collapsible behaviour corresponding to huge changes in the soil volume (Razouki et al. 1994).

In order to reduce the collapse index, improvement of the foundation behaviour would be a practical, more economical, and environmentally friendly method, a fundamental investigation that should be embraced to utilize a new technique in geotechnical design to be established in gypseous soil by using fly ash class F (10, 20, and 30%) and activator liquid (NaOH, KOH).

The geopolymer materials are unaffected by sulfate attack compared to cement. Sulfate attack can lead to loss of strength, expansion, sliding of surface layers, and ultimate disintegration when the sulfate ions intrude into the concrete and react with $\text{Ca}(\text{OH})_2$ in cement to generate more gypsum. In addition, there is a rise in CO_2 emission as a result of using cement or lime. In this study, alkali activators are used instead of cement and lime because the former have the ability to resist sulfate attack

whereas cement is attacked by solutions containing sulfates. Furthermore, the gel produced may not have $\text{Ca}(\text{OH})_2$ or mono-sulfo-aluminates due to being formed from materials when calcium content is low. Therefore, when gypseous soil that is stabilized with alkali activation is exposed to sulfate solution, it may not allow gypsum to expand and may even lessen the formation of ettringite in the matrix, meaning that the gel binder produced by alkali activation may not be affected by sulfate attack. The majority of the material in an alkali-activated binder is generally derived from industrial by-products. Therefore it is considered as an environmental friendly product. These binders have been identified as offering the potential for notable greenhouse gas emissions reduction when compared with Portland cement. Consequently, replacing ordinary Portland cement (OPC) or lime with alkali activator can largely reduce energy consumption and CO_2 emission. Therefore, the hypothesis behind using geopolymers [fly ash class F + activator liquid (NaOH or KOH)] instead of cement as stabilizer materials.

1.2 Problem Statement

Gypseous soil demonstrates volumetric changes due to dissolution of gypsum by water flow and increased permeability in the soil matrix, which causes uneven settlement or collapse, especially in wet state. Consequently, engineering construction on gypseous soil is extremely risky as several problems such as cracks, tilting, or differential settlement and composition failure may occur. Gypseous soils are widely distributed in arid and semi-arid areas of the world such as the Arabian peninsula, Russia, Armenia, the United States, Iraq, Iran, and Spain (Boyadgiev & Verheye, 1996; Casby-Horton *et al.*, 2015). So far, soil stabilization with cement is the most common treatment technique and it has been widely used to reduce the collapsibility of gypseous soils under engineering constructions, such as foundations and pavements. Nevertheless, the utilization of cement to treat soils with a large amount of gypsum often triggers side effects (Khatab, 1986).

In general, collapsible soils have porous textures with a high void ratio and relatively low densities. In dry state, they possess high apparent strength, but they are susceptible to large reductions in void ratio upon wetting (Jotisankasa 2005). When the soil is subjected to the wet condition, firstly the metastable texture collapses because the gypsum dissolves and the bonds between grains break down (Seleam, 1988). Then the soil particles become rearranged into a denser state of packing as the dissolved gypsum leaches out, and finally collapse occurs (Bolzon, 2010).

One of the practical techniques used to immobilize gypsum, preventing it from leaching out, is to stabilize it with cement. However, the major problem with stabilization of soil using cement is internal sulfate attack. Degradation of cement paste as a result of chemical reactions between hydrated Portland cement and sulfate ions from an outside source is known from crack propagation and expansion in the cement matrix. Sulfate attack can cause a significant reduction in the strength and mass due to disintegration of C-S-H (Hartell *et al.* 2011). Production of gypsum from the reaction of Ca^{+2} from C-S-H and calcium hydroxide with SO_4^{-2} is one of the major deterioration mechanisms in sulfate attack (Fallis 2013). Furthermore, exposure of

alumina containing hydrates to aggressive water leads to the formation of ettringite, which can also cause expansion and disintegration of the cement matrix. As in cement-stabilized gypseous soil, the sulfate attack is induced in the wet state of the soil due to the availability of a high content of sulfate ions in gypsum, which leads to disintegration of the stabilizing binder. The low integrity of the matrix, as a result, increases the permeability of the binder, facilitates infiltration of water, and increases leaching out of the gypsum. Increased porosity of the soil along with disintegration of stabilizers increases the collapse potential of the soil (Najah, Campus, and Pinang 2013).

Recently, geopolymer binders have been introduced as good replacements for cement due to their comparable mechanical properties along with greater resistance to chemical attacks (John L Provis 2014). The term “geopolymer” was initially coined by Davidovits in the 1970s and was later utilized to describe a class of solid materials synthesized through the reaction of an aluminosilicate powder with an alkaline solution. The geopolymer materials are generally industrial byproducts or other economical materials supplied in powder form and activated with an alkaline activator, which is usually a concentrated aqueous solution of alkali hydroxide, silicate, carbonate, or sulfate (Duxson et al. 2007). The strength gain in the geopolymer is related to the formation of geopolymer gel, which depends on rapid dissolution of the aluminosilicates and release of the tetrahedral units of $[\text{SiO}_4]^-$ and $[\text{AlO}_4]^-$ in the solution. These tetrahedral units are joined by sharing oxygen atoms instead of a polymeric precursor to form aluminosilicate hydrate (A-S-H) (John L. Provis 2014). Due to the energy efficiency and environmental friendly nature of the process as well as the excellent engineering properties, geopolymer binders are fast emerging as materials of choice for highly demanding civil-engineering applications.

The overarching purpose of this study is to use the low-calcium fly ash in gypseous soil stabilizing, which may reduce its collapsibility potential. Fly ash geopolymer may cover the gypsum particles in soil to prevent any contact between the gypsum particles and water. Furthermore, the absence of calcium in the binder structure can provide a sulfate-resistant property by which the vulnerability of the soil to the collapse potential (C_p) is reduced with an increase in gel binder amount. The findings of this study will help to understand the underlying mechanism by which geopolymer can control the internal sulfate attacks caused by the high quantity of gypsum in the soil matrix and to assess the collapse behaviour of gypseous soil stabilized with fly ash geopolymer.

1.3 Aim of the Research

The major aim of this present research is to attempt to stabilize gypseous soil characteristics using alkali activation method. Types of soils having different gypsum contents are used to study the effect of the alkali activator on improving the collapsibility and compressive and shear strength characteristics for various percentages of gypsum in the soil.

1.4 Objectives of the Research

The objectives include:

1. Characterizing the chemical, microstructural composition, assessing the compressive strength and sulfate-attack resistance of fly ash geopolymer binder with different activator types and molarities;
2. Determining the effective dose of the geopolymer such as the amount of fly ash and the type and molarity of activator liquid that must be mixed with soils having different quantities of gypsum;
3. Evaluating the changes in the geotechnical characteristics of the alkali-activated fly-ash treatment of the gypseous soil and its effect on the collapsibility characteristics of the soil after treatment;
4. Investigating the influence of sulfate SO_4^{2-} attack and its underlying mechanism of influencing the collapsibility characteristics, unconfined compressive strength, and permeability of the treated soil
5. Investigating an empirical model to estimate the collapsible index based on the amount of fly ash, molarity of activator liquid and the quantities of gypsum .

1.5 Scope of the Research

The research will concentrate on investigating the phenomenon of geopolymerization method in gypseous soil stabilization, considering the effects of this method on the collapsibility, chemical, and shear properties of gypseous soil before and after the treatment along with the effect of sulfate.

In this study, the behaviours of the alkali activator, industrial waste powder, and the chemical components during the reaction process were investigated based on the type of gel binder and its chemical properties. Disturbed and remoulded gypseous soil samples were collected for laboratory investigations. Artificial gypseous soil was prepared by adding CaSO_4 to the soil to make three types of gypseous soils (slightly, moderately, and highly gypseous). In this research, the gel binder is prepared from the industrial waste and the chemical solutions (fly ash + NaOH or KOH) used to stabilize the gypseous soil in the presence of different amounts of gypsum. The reaction and the underlying mechanism of the binder gel are investigated under exposure to sulfate attack on the geopolymer paste through the compressive strength test, mass loss test, X-ray diffraction (XRD), thermogravimetric analysis (TGA), Brunauer-Emmett-Teller (BET) surface area, scanning electron microscopy (SEM), and Energy-dispersive X-ray spectroscopy (EDX) analyses before and after soaking in sulfate solution. The effect of the stabilization method on the geotechnical characteristics of gypseous soil was investigated. On the other hand, the effect of internal sulfate attack was studied by soaking the soil samples before and after stabilization in laboratory tests, namely collapsibility, permeability-leaching (Rowe cell hydraulic pressure), unconfined compressive strength (UCS), and triaxial tests with XRD, SEM, and EDX analyses of the gypseous soil.

1.6 Significance of the Research

The application of the chemical treatment method to the stabilization of gypseous soil is performed by using alkali activators with industrial waste powder (fly ash class F) instead of the traditional additives such as cement or lime to prevent the problem of sulfate attack and improve the soil compressive strength by adding alkali activators with industrial waste powder (fly ash class F), which will play an important role in the future.

Preliminary reports from case studies show the beneficial role of alkali activation-stabilization techniques. Indeed, this technology can be used in situ by adding the activator to the soil and mix it for different gypsum contents. Some researchers applied this method to some types of soils such as expansive, clayey, and soft soils, and they showed remarkable improvement when the method was used.

On the other hand, every method may have some side effects such as changes in chemical compounds because of the alkali reaction, but there has been no research about the method's disadvantages until now. Furthermore, this technique is still in progress and the number of studies in this field is limited, so the disadvantages or side effects are unknown so far; however, there are some researches on the use of these materials in concrete instead of cement.

In fact, to understand the whole process and to gain more information and knowledge, some steps have to be followed. Firstly, the laboratory tests have done to show how the stabilization with alkali activation can affect and improve the soil properties. Secondly, these tests need to be repeated several times to find the optimum percentages of powder and alkali activator that give an acceptable improvement. Finally, the simulated data or results that emerge from these tests should be analysed. Hence, that will help in recognizing the advantages or disadvantages of the work.

The method of stabilization by alkali activation may be a workable technique in Iraq compared with other chemical techniques since it does not need any special equipment for mixing; not only that, but it is also beneficial to use ground granulated blast furnace slag (GGBS), a type of industrial waste that is available in Iraq. Indeed, the geopolymerization technique still has some un-investigated parts that need further attention and attempts to find a full explanation.

1.7 Thesis Organization

The thesis is presented in five chapters. Chapter One illustrates the importance of this study, including the aim, scope, and methodology with general information regarding the improvement of gypseous soil. Chapter Two presents a literature review on gypseous soil, including the formation and characteristics, collapse behaviour, shear strength characteristics, and studies of the treatment of gypseous soil. The third chapter describes the strategy used to equivalent the designated objectives of the research for

stabilizing gypseous soil. This chapter considers the materials used and classification tests as well as physical and chemical, collapse, shear, unconfined compression, soaking effect, permeability, compressive strength, and micro-structural tests. The fourth chapter reports the results of the testing programme together with the analysis and discussion of test results with drow curves. Chapter Five presents a brief summary of the research techniques and findings and then outlines simple specific conclusions of the study and recommendations for future studies.



REFERENCES

- Al-obaidi, Qasim A. J., Saad Farhan Ibrahim, and Tom Schanz. n.d. "Evaluation of Collapse Potential Investigated from Different Collapsible Soils." c:117–22.
- Al-Obaydi, M. A., I. M. Al-Kiki, and A. H. Al-Zubaydi. 2010. "Strength and Durability of Gypseous Soil Treated with Waste Lime and Cement." *Al-Rafidain Engineering* 18(1):2216–98.
- Aldaoood, A., M. Bouasker, and M. Al-Mukhtar. 2014. "Geotechnical Properties of Lime-Treated Gypseous Soils." *Applied Clay Science* 88-89:39–48. Retrieved (<http://dx.doi.org/10.1016/j.clay.2013.12.015>).
- Assi, Lateef N., Edward (Eddie) Deaver, Mohamed K. ElBatanouny, and Paul Ziehl. 2016. "Investigation of Early Compressive Strength of Fly Ash-Based Geopolymer Concrete." *Construction and Building Materials* 112:807–15. Retrieved (<http://linkinghub.elsevier.com/retrieve/pii/S095006181630294X>).
- Aziz, Hussein Yousif and Jianlin Ma. 2011. "Gypseous Soil Improvement Using Fuel Oil." 299–303.
- Bakharev, T. 2005. "Durability of Geopolymer Materials in Sodium and Magnesium Sulfate Solutions." *Cement and Concrete Research* 35(6):1233–46.
- Barazanji, A. F. 1973. "Gypseous Soil of Iraq." *State University of Ghent, Belgium*.
- Bolzon, Gabriella. 2010. "Collapse Mechanisms at the Foundation Interface of Geometrically Similar Concrete Gravity Dams." *Engineering Structures* 32(5):1304–11.
- Boyadgiev, T. G. and W. H. Verheye. 1996. "Contribution to a Utilitarian Classification of Gypsiferous Soil." *Geoderma* 74(3):321–38.
- Casby-Horton, Susan, Juan Herrero, and Nelson A. Rolong. 2015. *Gypsum Soils—Their Morphology, Classification, Function, and Landscapes*. Elsevier Ltd. Retrieved (<http://linkinghub.elsevier.com/retrieve/pii/S0065211314000091>).
- Cristelo, Nuno et al. 2015. "Assessing the Production of Jet Mix Columns Using Alkali Activated Waste Based on Mechanical and Financial Performance and CO₂ (eq) Emissions." *Journal of Cleaner Production* 2. Retrieved (<http://www.sciencedirect.com/science/article/pii/S0959652615004771>).
- Cristelo, Nuno, Stephanie Glendinning, Lisete Fernandes, and Amândio Teixeira Pinto. 2012. "Effect of Calcium Content on Soil Stabilisation with Alkaline Activation." *Construction and Building Materials* 29:167–74. Retrieved (<http://dx.doi.org/10.1016/j.conbuildmat.2011.10.049>).

- Cristelo, Nuno, Stephanie Glendinning, Lisete Fernandes, and Amândio Teixeira Pinto. 2013. "Effects of Alkaline-Activated Fly Ash and Portland Cement on Soft Soil Stabilisation." *Acta Geotechnica* 8(4):395–405.
- Cristelo, Nuno, Stephanie Glendinning, Tiago Miranda, Daniel Oliveira, and Rui Silva. 2012. "Soil Stabilisation Using Alkaline Activation of Fly Ash for Self Compacting Rammed Earth Construction." *Construction and Building Materials* 36:727–35. Retrieved (<http://linkinghub.elsevier.com/retrieve/pii/S0950061812004291>).
- Das, Sumanta et al. 2015. "Effective Properties of a Fly Ash Geopolymer: Synergistic Application of X-Ray Synchrotron Tomography, Nanoindentation, and Homogenization Models." *Cement and Concrete Research* 78:252–62. Retrieved (<http://dx.doi.org/10.1016/j.cemconres.2015.08.004>).
- Davidovits, Joseph. 2002. "30 Years of Successes and Failures in Geopolymer Applications. Market Trends and Potential Breakthroughs." in *Keynote Conference on Geopolymer Conference*.
- Design, Engineering. 2003. "G F G (1)." 04:1–4.
- Dimas, D., I. Giannopoulou, and D. Panias. 2009. "Polymerization in Sodium Silicate Solutions: A Fundamental Process in Geopolymerization Technology." *Journal of materials science* 44(14):3719–30.
- Dung, Nguyen Tien, Ta-Peng Chang, and Chun-Tao Chen. 2014. "Engineering and Sulfate Resistance Properties of Slag-CFBC Fly Ash Paste and Mortar." *Construction and Building Materials* 63:40–48. Retrieved (<http://www.sciencedirect.com/science/article/pii/S0950061814003262>).
- Duxson, P. et al. 2007. "Geopolymer Technology: The Current State of the Art." *Journal of Materials Science* 42(9):2917–33. Retrieved (<http://link.springer.com/10.1007/s10853-006-0637-z>).
- Duxson, P., G. C. Lukey, F. Separovic, and J. S. J. Van Deventer. 2005. "Effect of Alkali Cations on Aluminum Incorporation in Geopolymeric Gels." *Industrial & engineering chemistry research* 44(4):832–39.
- Duxson, Peter et al. 2005. "Understanding the Relationship between Geopolymer Composition, Microstructure and Mechanical Properties." *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 269(1):47–58.
- Fallis, A. .. 2013. *No Title No Title*.
- Fattah, Mohammed Y., Mohammad M. Al-ani, and Mahmoud T. Al-lamy. 2013. "Treatment of Collapse of Gypseous Soils by Grouting." *Proceedings of the institute of civil engineers ground Improvement* 166(GI1):32–43.

- Fattah, Mohammed Y., Hawraa H. M. Al-Musawi, and Firas a. Salman. 2012. "Treatment of Collapsibility of Gypseous Soils by Dynamic Compaction." *Geotechnical and Geological Engineering* 30(6):1369–87.
- Granizo, M. L. and M. T. Blanco. 1998. "Alkaline Activation of Metakaolin an Isothermal Conduction Calorimetry Study." *Journal of thermal analysis and calorimetry* 52(3):957–65.
- Guo, Xiaolu, Huisheng Shi, and Warren A. Dick. 2010. "Compressive Strength and Microstructural Characteristics of Class C Fly Ash Geopolymer." *Cement and Concrete Composites* 32(2):142–47.
- Hartell, Julie Ann, Andrew J. Boyd, M. Asce, and Christopher C. Ferraro. 2011. "Sulfate Attack on Concrete : Effect of Partial Immersion." 192(May):572–79.
- Van Jaarsveld, J. G. S. and J. S. J. Van Deventer. 1999. "Effect of the Alkali Metal Activator on the Properties of Fly Ash-Based Geopolymers." *Industrial & Engineering Chemistry Research* 38(10):3932–41.
- Jotisankasa, Apiniti. 2005. "Collapse Behaviour of a Compacted Silty Clay."
- Karako??, Mehmet Burhan, Ibrahim T??rkmen, M??sl??m Murat Mara??, Fatih Kantarci, and Ramazan Demirbo??a. 2016. "Sulfate Resistance of Ferrochrome Slag Based Geopolymer Concrete." *Ceramics International* 42(1):1254–60.
- Khattab, S. A. 1986. "Effect of Gypsum on Strength of Cement Treated Granular Soil and Untreated Soil."
- Kriven, Waltraud M., Jonathon L. Bell, and Matthew Gordon. 2003. "Microstructure and Microchemistry of Fully - Reacted Geopolymers and Geopolymer Matrix Composites." *Advances in Ceramic Matrix Composites IX, Volume 153* 227–50.
- Kumar, Sanjay, Rakesh Kumar, and S. P. Mehrotra. 2010. "Influence of Granulated Blast Furnace Slag on the Reaction, Structure and Properties of Fly Ash Based Geopolymer." *Journal of Materials Science* 45(3):607–15.
- Lizcano, Maricela, Hyun Soo Kim, Sandip Basu, and Miladin Radovic. 2012. "Mechanical Properties of Sodium and Potassium Activated Metakaolin-Based Geopolymers." *Journal of Materials Science* 47(6):2607–16.
- Mikheev, V. V, V. P. Petrukhin, and V. A. Krouik. 1973. "Properties of Saline Used in Construction." Pp. 133–38 in *Proceedings of 8th International Conference on Soil Mechanics and Foundation Engineering*, vol. 22.
- Najah, Lamyaa, Engineering Campus, and Pulau Pinang. 2013. "Collapsibility and Compressibility of Gypseous Soils." 7(7):196–99.

- Nashat, I. H. 1990. "Engineering Characteristics of Some Gypseous Soils in Iraq." *Civil Engineering Department, University of Baghdad, Baghdad, Iraq.*
- Nath, S. K., S. Maitra, S. Mukherjee, and Sanjay Kumar. 2016. "Microstructural and Morphological Evolution of Fly Ash Based Geopolymers." *Construction and Building Materials* 111:758–65. Retrieved (<http://linkinghub.elsevier.com/retrieve/pii/S0950061816301696>).
- Nguyen, Hoang Anh, Ta Peng Chang, Jeng Ywan Shih, Chun Tao Chen, and Tien Dung Nguyen. 2016. "Sulfate Resistance of Low Energy SFC No-Cement Mortar." *Construction and Building Materials* 102:239–43.
- Phair, J. W. and J. S. J. Van Deventer. 2002. "Characterization of Fly-Ash-Based Geopolymeric Binders Activated with Sodium Aluminate." *Industrial & engineering chemistry research* 41(17):4242–51.
- Pourakbar, Shahram, Bujang B. K. Huat, Mohammad Hamed Fasihnikoutalab, Afshin Asadi, and Van Impe. 2015. "Soil Stabilisation with." 1–12.
- Provis, John L. 2014. "Geopolymers and Other Alkali Activated Materials: Why, How, and What?" *Materials and Structures* 47:11–25.
- Provis, John L. 2014. "Geopolymers and Other Alkali Activated Materials: Why, How, and What?" *Materials and Structures* 47(1-2):11–25. Retrieved (<http://link.springer.com/10.1617/s11527-013-0211-5>).
- Razouki, S. S., R. R. Al-Omari, I. H. Nashat, H. F. Razouki, and S. Khalid. 1994. "The Problem of Gypsiferous Soils in Iraq." Pp. 7–33 in *Proceeding of the Symposium on Gypsiferous Soils and Their Effect on Structures, NCCL.*
- Salih, Moslih Amer, Abang Abdullah Abang Ali, and Nima Farzadnia. 2014. "Characterization of Mechanical and Microstructural Properties of Palm Oil Fuel Ash Geopolymer Cement Paste." *Construction and Building Materials* 65:592–603. Retrieved (<http://dx.doi.org/10.1016/j.conbuildmat.2014.05.031>).
- Sata, Vanchai, Apha Sathonsaowaphak, and Prinya Chindapasirt. 2012. "Resistance of Lignite Bottom Ash Geopolymer Mortar to Sulfate and Sulfuric Acid Attack." *Cement and Concrete Composites* 34(5):700–708. Retrieved (<http://dx.doi.org/10.1016/j.cemconcomp.2012.01.010>).
- Seleam, S. N. M. 1988. "Geotechnical Characteristic of Gypseous Sandy Soil Including the Effect of Contamination with Some Oil Products." *MSc. Thesis. University of Technology. Baghdad. Iraq.*
- Shi, Caijun, Dehui Wang, and Ali Behnood. 2012. "Review of Thaumassite Sulfate Attack on Cement Mortar and Concrete." *Journal of Materials in Civil Engineering* 24(12):1450–60. Retrieved ([http://ascelibrary.org/doi/abs/10.1061/\(ASCE\)MT.1943-5533.0000530](http://ascelibrary.org/doi/abs/10.1061/(ASCE)MT.1943-5533.0000530)).

- Sindhunata, J. S. J. Van Deventer, G. C. Lukey, and H. Xu. 2006. "Effect of Curing Temperature and Silicate Concentration on Fly-Ash-Based Geopolymerization." *Industrial & Engineering Chemistry Research* 45(10):3559–68.
- Škvára, František, Lubomír Kopecký, J. Nemecek, and ZDENĚK Bittnar. 2006. "Microstructure of Geopolymer Materials Based on Fly Ash." *Ceramics-Silikáty* 50(4):208–15.
- Sun, Peijiang and Hwai Chung Wu. 2013. "Chemical and Freeze-Thaw Resistance of Fly Ash-Based Inorganic Mortars." *Fuel* 111:740–45. Retrieved (<http://dx.doi.org/10.1016/j.fuel.2013.04.070>).
- Yang, Tao, Xiao Yao, and Zuhua Zhang. 2014. "Geopolymer Prepared with High-Magnesium Nickel Slag: Characterization of Properties and Microstructure." *Construction and Building Materials* 59:188–94.
- Zhang, Mo et al. 2015. "Calcium-Free Geopolymer as a Stabilizer for Sulfate-Rich Soils." *Applied Clay Science* 108:199–207. Retrieved (<http://linkinghub.elsevier.com/retrieve/pii/S0169131715000897>).
- Zhuang, Xiao Yu et al. 2016. "Fly Ash-Based Geopolymer: Clean Production, Properties and Applications." *Journal of Cleaner Production* 125:253–67. Retrieved (<http://dx.doi.org/10.1016/j.jclepro.2016.03.019>).
- Alsafi, S., Farzanda, N., Asadi, A., and Huat, B. B. (2016). Collapsibility potential of gypseous soil stabilized with fly ash geopolymer; characterization and assessment, *Building and Construction*, 3, 24–35 (published).