Improving Geotechnical Properties of Closed Landfills for Redevelopment Using Fly ash and Quicklime

By

Behnam Fatahi

A thesis submitted in fulfillment

of the requirements for the degree of

Doctor of Philosophy

Faculty of Engineering and Information Technology

University of Technology Sydney

March 2013

CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledge within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of candidate

Behnam Fatahi

Abstract

Many closed municipal solid waste (MSW) landfills are located near urban areas, even though originally established away from residential or commercial communities. Construction on top of closed landfills is generally a challenging task due to complex behaviour of creep, settlement and weak shear strength of waste materials. There is a high prospective to reuse these sites for redevelopment in spite of potential risk for human health and environment. The deep dynamic compaction technique is a common ground improvement technique due to its relatively economical and easy application for landfill sites. With deep dynamic compaction, large voids reduce and afterward other techniques such as cement, fly ash or lime grouting can further reduce the remaining smaller voids. Numerous studies have been conducted to treat and stabilise different types of problematic soils using fly ash with combination of lime. However, there is no comprehensive research on improvement of physical properties of MSW landfills using chemical admixtures such as fly ash and lime.

This study presents the experimental and numerical results of employing fly ash (class F) and quicklime (calcium oxide) in stabilisation of municipal solid wastes. The waste materials, used in this study, were collected from a closed landfill in the south-west of Sydney. The samples were prepared by integrating MSW, with a mixture of fly ash-quicklime with a ratio of 3:1 in percentages of 5, 10, 15 and 20 of fly ash by dry weight of the MSW. An array of experimental tests has been conducted on treated and untreated MSW samples including sieve analysis, Atterberg limits, compaction, permeability, large direct shear, unconfined compressive strength and consolidated-drained triaxial tests. Results of this investigation are evidence for a significant improvement in geotechnical properties of MSW materials, mixed with fly ash and quicklime. It has been found that the chemical stabilisation effectively increases the maximum dry density, the compressive strength, the shear strength parameters, the stiffness and the brittleness index, while decreases the compressibility, the permeability coefficient and the optimum moisture content of the MSW.

It has been quantified that by increasing fly ash-quicklime admixtures from 0 to 26.7% (0 to 20% fly ash) the internal friction angle increased from 29^o to 39^o and the cohesion intercept increased from 11 kPa to 30 kPa. Under an effective confining pressure of 300 kPa, the peak strength, the brittleness index and the Young's modulus at failure increased from 600 kPa to 1150 kPa, 0.13 to 0.35 and 5.5 MPa to 28 MPa, respectively, by addition of 26.7% fly ash-quicklime admixture. The coefficient of permeability for untreated specimen was 6.2×10^{-8} m/s and it was reduced to 3.2×10^{-8} m/s for specimens mixed with 26% fly ash-quicklime (under average confining pressure of 250 kPa). The compression and the secondary compression indices decreased from 0.33 to 0.23 and 0.052 to 0.033, respectively. Moreover, increasing the curing time enhanced the unconfined compressive strength, the friction angle, the cohesion and the preconsolidation pressure of the treated specimens, whereas no change in the permeability coefficient, the primary compression index and the secondary compression index were observed. The findings of this study may facilitate the calculations of the bearing capacity and settlement as well as the slope stability analysis of chemically treated closed landfill sites.

A finite element program, PLAXIS version 9, has been used to evaluate the settlement of the untreated and chemically treated landfill layers for 10 and 20 years after applying surcharge loads such as the traffic load. The effects of depth of stabilisation and the fly ash-quicklime content on vertical and horizontal displacements of the model have been investigated. Treated and untreated MSW parameters, used for the model, have been obtained from the results of the extensive laboratory program performed in this study. The numerical results indicated that treatment of MSW with fly ash-quicklime reduced the vertical displacement of the model under traffic load at the midpoint below the embankment. This reduction is more pronounced with higher fly ash-quicklime contents and deeper improvement of layers. For depths of 3m, 6m, 9m, 12m and 24m of the landfill improved with 26.7% fly ash-quicklime, the vertical settlements at the centreline of the embankment, 10 years after applying traffic load, were reduced by 20%, 32%, 40%, 46% and 58%, respectively. Horizontal displacements of the landfill model also significantly reduced in sections below the toe of the embankment, under traffic load. The reduction in horizontal displacements is more pronounced with improvement into deeper layers.

Acknowledgements

This PhD project could not have been possible without the support provided by numerous people. In particular, I would like to express my deepest appreciation and gratitude to:

My supervisor, Associate Professor Hadi Khabbaz, for his outstanding guidance, encouragement, wisdom and caring support provided throughout this project. It was an honour and a pleasure to be one of his students. Hadi's professional and far-thinking leadership ensured the steady progress, timely completion and high standard of this thesis. Over the years, Hadi's exceptional personality became a source of inspiration and a role model for my professional and personal development, which will be of guidance throughout my life. I thank him from the bottom of my heart for his invaluable advice and support given throughout the years.

Dr Behzad Fatahi, for his unfailing assistance, guidance and support over the past few years. His brilliant and sharp mind combined with his extensive technical knowledge, experience and dedication contributed largely to the success of this project.

The UTS laboratory staffs, Rami Haddad, David Hooper, Antonio Reyno, David Dicker, Peter Brown, Laurence Stonard and Richard Turnell, for their extensive assistance in conducting the experimental works. Special thank goes to Antonio Reyno, for his remarkable help in all technical matters conducting experimental testing in the soil laboratory.

The administrative and the support staff at UTS Faculty of Engineering and IT, Phyllis Agius, Craig Shuard, Van Lee and the IT support team for performing an excellent job in keeping the show running.

Sydney councils, particularly Bankstown, Fairfeild, Hornsby shire, Lane cove and Burwood Councils for their support in visiting the landfills and special thanks goes to Oliver Brown for permission of sampling from former Bankstown landfill site.

Dedication

I would like to dedicate this Doctoral dissertation to my family, particularly my wife Fouzieh Lotfi for her love, understanding and the sacrifice she has had to support my study, my father Dr Bahram Fatahi and my mother Monir Kheirandish for instilling in me the wisdom needed to complete this PhD project.

List of Publications

- Khabbaz H. and Fatahi B. (2010). "Chemical Stabilisation of Organic Soils Using Chemical Agents", *The Seventeenth Southeast Asian Geotechnical conference*, Taipei, Taiwan May 10~13, 2010

- Khabbaz, H. and Fatahi, B. (2010). "Ground Improvement of Closed Landfill Sites Using Chemical Stabilisation", *Proceedings of the Sixth International Congress on Environmental Geotechnics*, New Delhi, India, 88-93.

- Khabbaz, H. and Fatahi, B. (2011). "Chemical Stabilisation of Closed Landfill Sites Using Chemical Agents", *Proceedings of the XV European Conference on Soil Mechanics and Geotechnical Engineering*, Athens, Greece, 212-217

- Khabbaz, H. & Fatahi, B. (2012), "Stabilisation of Closed Landfill Sites by Fly Ash Using Deep Mixing Method", Grouting and Deep Mixing 2012, Louisiana, USA, February 2012 in *Proceedings of the Fourth International Conference on Grouting and Deep Mixing 2012*, ASCE, USA, pp. 417-426.

- Fatahi, B., Khabbaz, H. and Fatahi, B. (2012). "Mechanical Characteristics of Soft Clay Treated with Fibre and Cement", *Geosynthetics International, 19(3),* 252 –262.

- Fatahi, B., Khabbaz, H. Fatahi, B. (2012). "Application of Polypropylene and Carpet Fibres to Improve Mechanical Properties of Cement Treated Clay", *Proceedings of the International Symposium on Ground Improvement*, IS-GI Brussels TC 211, Vol. 2, 303-308.

- Fatahi, B. and Khabbaz, H. (2013). "Influence of Fly Ash and Quicklime Addition on Behaviour of Municipal Solid Wastes", *Journal of Soils and Sediments* (accepted/in-press) DOI 10.1007/s11368-013-0720-4

- Fatahi, B. and Khabbaz, H. (2013). "A numerical model to predict settlement of chemically stabilised landfill", The Third International Conference on Geotechnique, Construction Materials and Environment GEOMATE 2013

- Fatahi, B. and Khabbaz, H. (2013). "Influence of Fly Ash and Quicklime Addition on Permeability of Municipal Solid Wastes", *Journal of Soils and Sediments* (Submitted)

- Fatahi, B., Le, T. M., Fatahi, B. Khabbaz, H. (2013). "Shrinkage of Soft Clay Treated with Cement and Geofibres", *Geotechnical and Geological Engineering: International Journal* (accepted/in-press) DOI 10.1007/s10706-013-9666-y

- Fatahi, B., Fatahi, B. Le, T. M., Khabbaz, H. (2013). "Small-Strain Properties of Soft Clay Treated with Fibre and Cement", *Geosynthetics International* (submitted/under review)

Table of Contents

Abstract ii

Acknowledgements iv

List of Publications vi

List of Figures xiii

List of Tables xxii

CHAPTER 1 1

1 Introduction 1

1.1 Introduction 1

1.2 Statement of the problems 2

1.3 Research Background 3

1.3.1 Improvement Techniques 3

1.3.2 Chemical Stabilisation 3

1.4 Research Scope and Objectives 4

1.5 Outline of Thesis 6

CHAPTER 2 8

2 Literature Review 8

2.1 Waste Mechanics 8

2.2 Waste Components 9

2.3 Landfill Components 9

2.3.1 Liner System 9

2.3.2 Leachate Collection And Removal System 10

2.3.3 Gas Collection and Control System 10

2.3.4 Final Cover System 10

2.3.5 Composite Liners 11

2.4 Unit Weight of Municipal Solid Waste 11

2.4.1 Introduction 11

2.4.2 Importance of MSW Unit Weight in Engineering Analyses 12

2.4.3 Methods Used to Estimate MSW Unit Weight 14

2.4.4 Unit Weight Model for Municipal Solid Waste 15

2.4.5 Effect of Compaction on Unit Weight of MSW 16
2.4.6 Effect of Depth on the Unit Weight of MSW 18
2.4.7 Effect of Moisture Content on Unit Weight of MSW................................... 18
2.5 Compressibility.. 19
2.5.1 Introduction 19
2.5.2 Mechanism of Waste Settlement.. 19
2.5.3 Primary Compression 21
2.5.4 Completion of Primary Settlement Time 21
2.5.5 Secondary Compression 22
2.5.6 Total Compression 23
2.5.7 Influencing Factors... 23
2.5.8 Settlement Estimation Methods for MSW Landfills..................................... 24
2.5.8.1 Sowers method.. 24
2.5.8.2 Rheological model 27
2.5.8.3 Power creep model 27
2.5.8.4 Hyperbolic function model 27
2.5.9 Categories of Secondary Settlement 28
2.5.9.1 Settlement under self-weight: 28
2.5.9.2 Settlement under external loads:.. 29
2.6 Shear Strength of MSW... 34
2.6.1 Introduction 34
2.6.2 Background 35
2.6.3 Effect of particles orientation... 44
2.6.4 Effect of Normal stress.. 45
2.6.5 Back Calculations from Field Cases 47
2.6.6 Limitations 49
2.7 Hydraulic Conductivity 50
2.7.1 Introduction 50
2.7.2 Saturated Flow 51
2.7.3 Background 52
2.7.4 Influence of Effective Stress and Waste Density on Hydraulic Conductivity 54

2.7.5 Effect of Waste Degradation 56
2.7.6 Waste Anisotropy 57
2.8 Improvement Techniques for MSW landfills 59
2.9 Chemical Stabilisation 59
2.9.1 Lime Stabilisation 60
2.9.2 Fly ash Stabilisation 61
2.9.3 Lime/Fly ash Stabilisation 65
2.10 Summary 75
CHAPTER 3 79
3 Geotechnical Characterisation of the Collected MSW Samples 79
3.1 Introduction 79
3.2 Classes of Landfill 79
3.3 Number of Landfills by Type of Waste Acceptance in Australia 80
3.4 Sampling Permission 81
3.5 Sites Visits 81
3.5.1 Blackman Park – Lane Cove Council 81
3.5.2 Wangal Park – Burwood Council 82
3.5.3 Dartford Road Landfill, Thornleigh – Hornsby Shire Council 83
3.5.4 Brenan Park – Fairfield City Council 84
3.6 Bankstown Landfill Site and Test pits Locations 85
3.7 In-situ MSW Characterisation in Bankstown Former Landfill 87
3.8 Primary Geotechnical MSW Characterisation 88
3.9 Excavations and Samples Collection 88
3.10 Geotechnical Characterisation of MSW 91
3.11 Moisture Content and Organic Content of MSW – Material Loss 92
3.11.1 Background 92
3.11.2 Definitions 92
3.11.3 Material Loss Testing Procedure 93
3.11.4 Results of Moisture Content and Organic Content for this Research 94
3.12 Waste Composition 95
3.13 Sieve Analysis and Characterisation of Smaller Fraction 95

3.14 Summary 99
CHAPTER 4 101
4 Materials, Sample Preparation and Laboratory Testing Program 101
4.1 Introduction 101
4.2 Materials 101
4.2.1 Municipal Solid Waste 101
4.2.2 Fly ash 102
4.2.2.1 Chemical Composition of Fly Ash 104
4.2.3 Lime 104
4.2.3.1 Activation of Fly ash with Lime 106
4.3 Compaction Tests 107
4.4 Particle Size Limitation 109
4.5 Ratio of Fly Ash and Quicklime in Soil Stabilisation 110
4.6 Mixing of Materials 110
4.7 Sample Preparation 112
4.8 Experimental Program 113
4.8.1 Unconfined Compressive Strength Tests 113
4.8.2 Direct Shear Tests 117
4.8.2.1 Description of the Large Direct Shear Box Device 118
4.8.2.2 Large Direct Shear Testing Program 120
4.8.3 Hydraulic Conductivity 121
4.8.3.1 Triaxial Hydraulic Conductivity Procedures for Recompacted 121
4.8.3.2 Constant Head Hydraulic Conductivity Tests 123
4.8.4 Triaxial Test 126
4.8.4.1 Triaxial and Consolidation Specimen Preparation and Testing Procedures 126
4.9 Summary 131
CHAPTER 5 133
5 Experimental Results and Discussion 133
5.1 Introduction 133
5.2 Unconfined Compressive Tests 133

5.2.1 Effect of the Content of Fly ash-Quicklime ... 133
5.2.2 Effect of Curing Time ... 136
5.3 Direct Shear Test ... 139
5.3.1 Direct Shear Tests Results ... 139
5.3.2 Effect of Curing Time ... 139
5.3.3 Stress-Strain Behaviour ... 141
5.4 Permeability Test ... 148
5.4.1 Effect of Fly ash-Quicklime Content ... 148
5.4.2 Effect of Curing Time ... 149
5.4.3 Permeability Results from Consolidation Tests Using Triaxial Apparatus ... 150
5.4.3.1 Coefficient of Consolidation ... 150
5.4.3.2 Hydraulic Conductivity ... 151
5.4.3.3 Permeability Change Index ... 155
5.5 Consolidated Drained Triaxial Test Results ... 158
5.5.1 Stress-Strain Behaviour ... 158
5.5.2 Shear Strength Parameters ... 164
5.5.3 Modulus of Elasticity ... 166
5.5.4 Brittleness Index ... 168
5.5.5 Primary Compression ... 169
5.5.6 Secondary Compression ... 176
5.6 Summary ... 180
CHAPTER 6 ... 182
6 Numerical Analysis to Predict the Settlement of Closed Landfills ... 182
6.1 Introduction ... 182
6.2 Finite Element Modeling ... 183
6.3 Mesh Generation and Boundary Conditions ... 183
6.4 Adopted Material Models ... 185
6.5 Material Parameters ... 191
6.6 Analysis Type ... 194
6.7 Results and Discussion ... 195
6.7.1 Vertical Settlement 10 Years after Applying Traffic Load ... 195

6.7.2 Vertical Settlement 20 Years after Applying the Traffic Load:.................. 199

6.7.3 Horizontal Displacement 10 Years after Applying the Traffic Load........... 204

6.8 Summary.. 208

CHAPTER 7 209

7 Summary and Conclusions 209

7.1 Summary.. 209

7.2 Concluding Remarks 211

7.3 Recommendation for Further Study 216

References 218

Appendix 231

List of Figures

Figure 1.1 Payatas landfill in Philippin (photo by: Scott Merry) 3

Figure 2.1 Physical meaning of the hyperbolic parameters α and β (Zekkos 2005) 16

Figure 2.2 Relationships between density and average vertical stress. Trend lines shown are based on average measured values (Powrie and Beaven 1999, taken from Dixon and Jones 2004) 18

Figure 2.3 Occurrence of settlement mechanisms and temporal classifications adopted by selected publications. (Modified after McDougall 2011) 20

Figure 2.4 *Landfill settlement vs. log time from field case histories (Bjarngard and Edgers1990)* 22

Figure 2.5 Mechanisms and factors influencing landfill settlement. (Modified after McDougall 2011) 24

Figure 2.6 Time dependent secondary settlement model extending to three stages as proposed by Hossain and Gabr (2005) 31

Figure 2.7 Comparison of predicted and observed field settlement for bioreactor landfills, (Hossain and Gabr 2005) 32

Figure 2.8 Measured and predicted strains with stress applied to fresh waste specimen and decomposed waste specimen (Chen et al 2010). 33

Figure 2.9 Variation of strain with time (Chen et al 2010) 33

Figure 2.10 Variation of strain with time (Chen et al 2010) 34

Figure 2.11 Results of laboratory CU triaxial tests on reconstituted saturated MSW (Caicedo et al. 2002b). 37

Figure 2.12 Representative results from consolidated drained triaxial tests on partially saturated MSW with unit weight of 12 kN/m3 and water content of 67% (Vilar and Carvalho, 2002). 39

Figure 2.13 Representative results from consolidated drained triaxial tests on saturated MSW with unit weight of 12 kN/m3 (Vilar and Carvalho, 2002). 40

Figure 2.14 Shear strength envelopes for triaxial specimens on MSW. Unit weight 12kN/m3 both saturated and unsaturated (Vilar and Carvalho, 2002). 41

Figure 2.15 Stress-strain relationships from triaxial tests performed by Gomes et al. (2002) 42

Figure 2.16 Responses of MSW in monotonic triaxial compression testing for specimens with varying waste compositions (Bray et al. 2009). 44

Figure 2.17 Stress-displacement response for MSW specimens with plastic reinforcement oriented at different angles at a normal stress of 50 kPa (Bray et al. 2009). 45

Figure 2.18 Direct shear strength of Tri-Cities landfill MSW: (a) curved strength envelope for samples with varying waste composition, and (b) decrease in secant friction angle with increasing normal stress assuming c = 15 kPa (Bray et al. 2009.) 46

Figure 2.19 Response of MSW with 62% less than 20 mm material in direct shear testing loaded at two displacement rates (Bray et al. 2009). 47

Figure 2.20 Shear strength envelope (Kavazanjian et al. 1995). 48

Figure 2.21 Vertical hydraulic conductivity against (a) the logarithm of the vertical effective stress in first loading; (b) the drainable porosity; and (c) density, for four waste types (data from Beaven 2000 and Hudson et al. 2001) 54

Figure 2.22 Summary of relationships between vertical hydraulic conductivity and waste dry density.(Beaven et al. 2011) 56

Figure 2.23 kh : kv versus applied stress for sample AG1. (Beaven et al. 2011) 57

Figure 2.24 kh : kv versus applied stress for sample DN1. (Beaven et al. 2011) 58

Figure 2.25 Compaction curves of blended CCR-stabilised clay (Horpibulsuk et al. 2012) 67

Figure 2.26 Strength development in blended CCR-stabilized clay at OWC and 5% binder for different CCR:Fly ash ratios (Horpibulsuk et al. 2012) 67

Figure 2.27 Strength development in blended CCR-stabilized clay at OWC and 10% binder for different replacement ratios (Horpibulsuk et al. 2012) 68

Figure 2.28 Unconfined compressive strength of soils stabilised with a blend of 15% coal fly ash and 3% limestone dust relative to those of control soils (Brooks et al. 2011) 69

Figure 2.29 UCS of lime and CFA mixes (Singh et al. 2010) 69

Figure 2.30 Resilient modulus for stabilised soils (σd = 42 kPa and σ3=13 kPa) (Singh et al. 2010) 70

Figure 2.31 Water content versus compressive strength (Han-bing et al. 2009). 70

Figure 2.32 Water content versus deformation modulus (Han-bing et al. 2009). 71

Figure 2.33 Relationships between unconfined compressive strength and fly ash content (Shao et al. 2008) 71

Figure 2.34 Dry density versus lime (%) at different % of fly ash (Kumar et al. 2007) 72

Figure 2.35 Optimum moisture content (%) versus lime (%) at different % of fly ash (Kumar et al. 2007) 73

Figure 2.36 Variation of unconfined compressive strength with % of lime for different % of fly ash (after 7 days curing) (Kumar et al. 2007) 74

Figure 2.37 Variation of unconfined compressive strength with % of lime for different % of fly ash (after 14 days curing) (Kumar et al. 2007) 74

Figure 2.38 Variation of unconfined compressive strength with % of lime for different % of fly ash (after 28 days curing) (Kumar et al. 2007) 74

Figure 3.1 Blackman park - waterlogged after rainfall 82
Figure 3.2 Wangal park - Wetland Surrounded by Fence 83
Figure 3.3 Dartford road landfill - golf driving range under construction 84
Figure 3.4 Brenan Park 84
Figure 3.5 Location of the former Bankstown landfill (courtesy of Google Maps) 85
Figure 3.6 Plan view of the former Bankstown landfill and test pits locations 86
Figure 3.7 Location of TP1 in former Bankstown landfill 86
Figure 3.8 Digging the test pit using a backhoe 89
Figure 3.9 Side view of the excavated test pit 89
Figure 3.10 View of the primary waste components 89
Figure 3.11 View of the primary waste components 90
Figure 3.12 Drums filled from the first borehole 90
Figure 3.13 Filling drums with excavated waste materials using a backhoe 90
Figure 3.14 Placement of representative samples of waste in the drums 91
Figure 3.15 Placement of the soil fraction in plastic bags and in the drum 91
Figure 3.16 View of furnace heated at 440 degrees Celsius 93
Figure 3.17 View of furnace used for estimation of organic content of waste material 94
Figure 3.18 Samples of less than 19 mm material in furnace 94
Figure 3.19 Waste material included all particle size before sieving 96
Figure 3.20 View of the larger than 19 mm waste material (retained on the sieves) 96
Figure 3.21 Dry sieve analyses of finer than 19 mm fraction 97
Figure 3.22 Sieve analysis process 97
Figure 3.23 Processing of the waste through the 19 mm sieve. 97
Figure 3.24 Dry sieve analyses of finer than 9 mm fraction 98
Figure 3.25 Remaining fraction of processed material on different sieves 98
Figure 3.26 Small wood particles on one of the sieves 99
Figure 4.1 Eraring Fly Ash used as an additive to waste material 103
Figure 4.2 View of quicklime used as an additive to waste material 105
Figure 4.3 View of compaction test equipments 107
Figure 4.4 Filling the compaction mould with smaller than 9mm decomposed waste material 108
Figure 4.5 Compacted waste material with mould after compaction completed 108
Figure 4.6 Waste material included all particle size before sieving 109

Figure 4.7 Smaller than 19 mm waste material before mixing with additives 111

Figure 4.8 Mixture procedure of waste material with fly ash and quicklime 111

Figure 4.9 View of sample of waste material after mixing with fly ash and quicklime 111

Figure 4.10 Moisture content absorption ratio of treated MSW samples 112

Figure 4.11 Moisture content of treated MSW samples 112

Figure 4.12 The split mould used for the unconfined compressive strength test sample preparation 114

Figure 4.13 View of prepared samples for unconfined compressive strength test with various fly ash – quicklime content 115

Figure 4.14 View of specimen with 13% additives (10% fly ash + 3.3% quicklime) 116

Figure 4.15 A specimen with 20% additives before unconfined compressive strength test 116

Figure 4.16 A specimen with 13% additives after completion of unconfined compressive strength test 117

Figure 4.17 A specimen with 26% additives after completion of unconfined compressive strength test 117

Figure 4.18 View of the direct shear device used for the performance of the tests 119

Figure 4.19 The crane used for lifting the normal force and applying to the sample 119

Figure 4.20 3 LVDTs for the measurement of the horizontal and vertical displacements 119

Figure 4.21 The hammer used for the specimen compaction in shear box at the University of Technology Sydney 120

Figure 4.22 A compacted waste material in a mould prepared for the permeability test . 124

Figure 4.23 Using high permeable fibre to prevent sample particles movement into drainage layers 125

Figure 4.24 Drainage layer on top (and bottom) of the sample 125

Figure 4.25 Prepared sample for permeability tests 125

Figure 4.26 An experimental setup for permeability tests 126

Figure 4.27 The triaxial sample preparation mould and the extruder 130

Figure 4.28 The automated triaxial apparatus during a CD test on a MSW sample 130

Figure 4.29 A snapshot of a failed waste sample after completion of a CD Triaxial test . 131

Figure 5.1 Unconfined compressive strength of untreated and treated MSW specimen with different fly ash-quicklime contents 134

Figure 5.2 Engineering properties of organic soil–fly ash mixtures as a function of fly ash percentage in the mixture (Tastan et al. 2011) 136

Figure 5.3 Effect of curing time on unconfined compressive strength of MSW specimens 137

Figure 5.4 Unconfined compressive strength of fly ash versus curing period for unsoaked specimens with varying percentages of lime (Ghosh and Subbarao 2007) 138

Figure 5.5 Unconfined compressive strength of fly ash versus curing period for soaked and unsoaked specimens with varying percentages of lime and (a) 0.5%; (b) 1.0% gypsum (Ghosh and Subbarao 2007) 138

Figure 5.6 Shear strength envelope from the results of direct shear test on untreated and treated MSW specimens with different fly ash-quicklime contents 140

Figure 5.7 Effect of curing time on shear strength envelope of treated MSW specimens with 20% fly ash-quicklime 140

Figure 5.8 Shear strength of untreated MSW specimen in direct shear test under different normal stresses 142

Figure 5.9 Vertical displacement vs. horizontal displacement for untreated MSW specimen under different normal stresses 142

Figure 5.10 Shear strength of treated MSW specimen mixed with 13.3% fly ash-quicklime in direct shear test under different normal stresses 143

Figure 5.11 Vertical displacement vs. horizontal displacement for treated MSW specimen mixed with 13.3% fly ash-quicklime under different normal stresses 143

Figure 5.12 Shear strength of treated MSW specimen mixed with 20% fly ash-quicklime in direct shear test under different normal stresses 144

Figure 5.13 Vertical displacement vs. horizontal displacement for treated MSW specimen mixed with 20% fly ash-quicklime under different normal stresses 144

Figure 5.14 Shear strength of treated MSW specimen mixed with 26.7% fly ash-quicklime in direct shear test under different normal stresses 145

Figure 5.15 Vertical displacement vs. horizontal displacement for treated MSW specimen mixed with 26.7% fly ash-quicklime under different normal stresses 145

Figure 5.16 Large-scale DS test results on MSW from Canada (Landva and Clark, 1990). 146

Figure 5.17 Recommended static shear strength of MSW based primarily on direct shear tests and field observations of static slope stability (Bray et al. 2009). 147

Figure 5.18 Results of in situ direct shear tests on MSW (Caicedo et al. 2002a). 148

Figure 5.19 Coefficient of permeability of untreated and treated MSW specimens under 7 , 28 and 93 days curing time 149

Figure 5.20 Coefficient of consolidation of MSW specimens for different fly ash-quicklime contents under various effective confining pressures 151

Figure 5.21 Coefficient of permeability of MSW specimens for different fly ash-quicklime contents under various effective confining pressures 154

Figure 5.22 Coefficient of permeability of MSW specimens for different fly ash-quicklime contents under various effective confining pressures 154

Figure 5.23 Void ratio-permeability relationship of untreated MSW specimen 155

Figure 5.24 Void ratio-permeability relationship of treated MSW specimen with 6.7% fly ash-quicklime 156

Figure 5.25 Void ratio-permeability relationship of treated MSW specimen with 13.3% fly ash-quicklime 156

Figure 5.26 Void ratio-permeability relationship of treated MSW specimen with 20% fly ash-quicklime 157

Figure 5.27 Void ratio-permeability relationship of treated MSW specimen with 26.7% fly ash-quicklime 157

Figure 5.28 Void ratio-permeability relationship of untreated and treated MSW specimen with different fly ash-quicklime contents 158

Figure 5.29 Stress-strain-volumetric response of untreated MSW specimens 160

Figure 5.30 Stress-strain-volumetric response of treated MSW specimens with 6.7% fly ash-quicklime content 160

Figure 5.31 Stress-strain-volumetric response of treated MSW specimens with 13.3% fly ash-quicklime content 161

Figure 5.32 Stress-strain-volumetric response of treated MSW specimens with 20% fly ash-quicklime content 161

Figure 5.33 Stress-strain-volumetric response of treated MSW specimens with 26.7% fly ash-quicklime content 162

Figure 5.34 Stress-strain responses of treated and untreated MSW specimens with different percentages of fly ash-quicklime at effective confining pressure of 100 kPa 162

Figure 5.35 Stress-strain responses of treated and untreated MSW specimens with different percentages of fly ash-quicklime at effective confining pressure of 200 kPa 163

Figure 5.36 Stress-strain responses of treated and untreated MSW specimens with different percentages of fly ash-quicklime at effective confining pressure of 300 kPa 163

Figure 5.37 Stress–strain response of fly ash, 7 and 28 days curing (Ghosh and Subbarao 2007) 164

Figure 5.38 Stress–strain response of fly ash with 10% lime and 1% gypsum, 7 days curing (Ghosh and Subbarao 2007) 164

Figure 5.39 Peak-strength envelopes of untreated and treated MSW specimens 165

Figure 5.40 Residual-strength envelopes of untreated and treated MSW specimens 166

Figure 5.41 Variation of Young's modulus at 50% failure stress for untreated and treated MSW specimens under different effective confining pressures. 167

Figure 5.42 Variation of Young's modulus at failure stress for untreated and treated MSW specimens under different effective confining pressures. 167

Figure 5.43 Variation of stiffness ratio of untreated and treated MSW specimens under different effective confining pressures. 168

Figure 5.44 Effect of fly ash-quicklime contents on brittleness index of MSW specimens under different effective confining pressures 169

Figure 5.45 Primary compression of untreated and treated MSW specimens with different fly ash-quicklime contents 170

Figure 5.46 Primary compression of treated MSW specimens with 20% fly ash-quicklime for 28 and 93 days curing period 171

Figure 5.47 Effect of fly ash-quicklime contents on compression index of MSW specimens 172

Figure 5.48 Void ratio versus pressure of raw and 6% stabilised Alloway Clay (Okoro et al. 2011) 173

Figure 5.49 Void ratio versus pressure curves of raw and 10% CFA-stabilised Made Land (Okoro et al. 2011) 173

Figure 5.50 Variation of Cc for both expansive and nonexpansive clays (Phanikumar and Sharma 2007) 174

Figure 5.51 e-log p curves of expansive clay specimens (Phanikumar and Sharma 2007) 175

Figure 5.52 e-log p curves of nonexpansive clay (Phanikumar and Sharma 2007) 175

Figure 5.53 Primary and secondary compression of MSW specimens when effective confining pressure increased from 200 kPa to 300 kPa 176

Figure 5.54 Volumetric strain of treated and untreated MSW specimens during primary and secondary compression (when effective confining pressure increased from 200 kPa to 300 kPa) 177

Figure 5.55 Effect of fly ash-quicklime contents on the secondary compression index of MSW specimens 178

Figure 5.56 Effect of curing time on primary and secondary compression of MSW specimens when effective confining pressure increased from 200 kPa to 300 kPa 179

Figure 5.57 Effect of fly ash on secondary consolidation (Phanikumar and Sharma 2007) 180

Figure 6.1 Cross-section of the numerical model 183

Figure 6.2 Dimensions of the model 184

Figure 6.3 15-nodded triangle elements, used in the modeling 184

Figure 6.4 Cross-section of generated mesh 184

Figure 6.5 Closer view of generated mesh 185

Figure 6.6 Consolidation and creep behaviour in standard Oedometer tests (Wehnert 2000) 188

Figure 6.7 Logarithmic relationship between volumetric strain and mean stress including creep (after Wehnert 2000) 189

Figure 6.8 Yeild surface of the SS-model in p'-q plane (after Wehnert 2000) 191

Figure 6.9 Vertical displacement for untreated landfill 10 years after applying traffic load 196

Figure 6.10 Vertical displacement for 3-m treated with 26.6% fly ash-quicklime 10 years after applying traffic load 196

Figure 6.11 Vertical displacement for 6-m treated with 26.6% fly ash-quicklime 10 years after applying traffic load 197

Figure 6.12 Vertical displacement for 9-m treated with 26.6% fly ash-quicklime 10 years after applying traffic load 197

Figure 6.13 Vertical displacement for 12-m treated with 26.6% fly ash-quicklime 10 years after applying traffic load 198

Figure 6.14 Vertical displacement for 24-m treated with 26.6% fly ash-quicklime 10 years after applying traffic load 198

Figure 6.15 Vertical settlement versus time for 3-m improved landfill with various fly ash-quicklime contents under traffic load 200

Figure 6.16 Vertical settlement versus time for 6-m improved landfill with various fly ash-quicklime contents under traffic load 200

Figure 6.17 Vertical settlement versus time for 9-m improved landfill with various fly ash-quicklime contents under traffic load 201

Figure 6.18 Vertical settlement versus time for 12-m improved landfill with various fly ash-quicklime contents under traffic load 201

Figure 6.19 Vertical settlement versus time for 24-m improved landfill with various fly ash-quicklime contents under traffic load 202

Figure 6.20 Vertical settlement versus time for landfill treated with 6.7% fly ash-quicklime content under traffic load 202

Figure 6.21 Vertical settlement versus time for landfill treated with 13.3% fly ash-quicklime content under traffic load 203

Figure 6.22 Vertical settlement versus time for landfill treated with 20% fly ash-quicklime content under traffic load 203

Figure 6.23 Vertical settlement versus time for landfill treated with 26.7% fly ash-quicklime content under traffic load 204

Figure 6.24 Horizontal displacements for untreated landfill 10 years after applying load 205

Figure 6.25 Horizontal displacement for 6-m treated with 26.6% fly ash-quicklime 10 years after applying load 205

Figure 6.26 Horizontal displacement for 12-m treated with 26.6% fly ash-quicklime 10 years after applying load 206

Figure 6.27 Horizontal displacement for 24-m treated with 26.6% fly ash-quicklime 10 years after applying load 206

Figure 6.28 Horizontal displacement versus depth for the landfill treated with 26.7% fly ash-quicklime content in various improvement depths at a section below the toe of embankment.. 207

Figure 6.29 Horizontal displacement versus depth for 9-m improved landfill treated with various fly ash-quicklime contents at a section below the toe of embankment................. 207

List of Tables

Table 1.1 Per capita waste generation for Australia, estimated, 2006/07 (Hyder Consulting 2008) 2

Table 2.1 Engineering properties of MSW required for design (from Dixon and Jones, 2005). 12

Table 2.2 Hyperbolic parameters for different compaction effort and amount of soil cover (Zekkos 2005) 16

Table 2.3 Statistical summaries of bulk unit weight data for fresh waste (after Fassett et al. 1994) 17

Table 2.4 Bulk unit weights from international literature (after Dixon and Jones 2005) ... 17

Table 2.5 Recommended Values of Cα Parameters (Sharma 2007) 29

Table 2.6 Model parameters for settlement prediction (Hossain and Gabr 2005) 31

Table 2.7 MSW shear strength laboratory tests results from literature 36

Table 2.8 Summary of tests relating the vertical hydraulic conductivity of MSW type materials to dry density. 55

Table 2.9 kh :kv ratios obtained by laboratory testing of wastes. 57

Table 3.1 Two basic landfill classes 80

Table 3.2 Approximate number of landfill by class and State 80

Table 3.3 Depth and characterisation of test pits 85

Table 3.4 Moisture content and organic content results of collected waste samples 95

Table 4.1 Chemical composition of Eraring fly ash 104

Table 4.2 Compaction test results for untreated and treated MSW samples (particles smaller than 9 mm) 108

Table 4.3 Compaction test results for untreated and treated MSW samples (particles smaller than 19 mm.) 109

Table 4.4 Ranges of additives to MSW samples 113

Table 4.5 Summary of unconfined compressive strength specimens and tests performed. 115

Table 4.6 Summary of large direct shear specimens and tests performed at the University of Technology Sydney 121

Table 4.7 Summary of permeability test specimens through consolidation of specimen in triaxial cell 122

Table 4.8 summary of permeability test specimens and their details 124

Table 4.9 Summary of triaxial specimens and tests performed 128

Table 4.10 Summary of consolidation specimens and tests performed 129

Table 5.1 Results of unconfined compressive strength tests 135

Table 5.2 Summary of large direct shear tests results 141

Table 5.3 Effect of fly ash on compaction Behavior, and hydraulic conductivity (Modified after Kumar and Sharma 2004) 150

Table 5.4 Summary of permeability test results through consolidation of specimen in triaxial cell 153

Table 5.5 Results of Peak and residual principal stress difference in triaxial compression test 159

Table 5.6 Peak and residual strength and elastic parameters for untreated and treated MSW in triaxial compression test. 165

Table 5.7 Variation of primary compression index for MSW specimen treated with different fly ash-quicklime content and curing time 171

Table 5.8 A summary of swell and compression indices of raw and stabilised soils. (after Okoro et al. 2011) 173

Table 5.9 Variation of secondary compression index for MSW specimen treated with different fly ash-quicklime content and curing time 178

Table 5.10 Effect of Fly Ash on Coefficient of Secondary Consolidation, Cα (Phanikumar and Sharma 2007) 180

Table 6.1 Parameters for soft soil creep model in FEM analysis 193

Table 6.2 Model parameters used for cover layer and road embankment 194

Table 6.3 Fly ash-quicklime contents and depths of treatment for closed landfill model . 194

Table 6.4 Vertical displacement of the landfill model 10 years after applying traffic load 195

Table 6.5 Vertical displacements of the landfill model, 20 years after applying the traffic load 199