



Enhancing the Engineering Properties of Expansive Soil Using Bagasse Ash, Bagasse Fibre and Hydrated Lime

A thesis in fulfilment of the requirement
for the award of the degree

Doctor of Philosophy

from

University of Technology Sydney (UTS)

by

Liet Chi Dang, BEng., MEng.

School of Civil and Environmental Engineering
Faculty of Engineering of Information Technology

January 2019

CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in 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 acknowledged 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.

Production Note:
Signature removed prior to publication.

Signature of candidate

Liet Chi Dang

Date: January 2019

DEDICATION

I would like to deeply dedicate this thesis to my family, especially my respective parents, Chien Minh Dang and Oanh Thi Truong, for their sacrifices, endless love, inspiration and hard working, my brother Cong Chi Dang and my sister Hanh Nhu Thi Dang for imparting to me the wisdom, the strength and the determination necessary to fully finish my PhD research study.

ABSTRACT

Expansive soils exhibit massive volume change against fluctuations of moisture content. Shrinkage and expansion of soil can commonly take place near the ground surface, where it is directly subjected to seasonal and environmental variations. Construction of civil engineering structures on expansive soils is highly risky, as this type of soil is susceptible to seasonal drying and wetting cycles, causing significant deformations. Frequent soil movements can generate cracks and damage residential buildings, roads, and other civil structures directly placed on this type of problematic soil. Many efforts have been applied in practice to overcome the adverse effects of expansive soil including replacement of existing expansive soil with non-expansive soil, maintaining a constant moisture content, and ground improvement techniques such as the application of granular pile-anchors, sand cushion technique, and belled piers, and soil stabilisation with chemical agents (e.g. lime or cement) and so on. On top of that, lime stabilisation is the most commonly used method for controlling the shrink-swell behaviour of expansive soil due to seasonal variations. Lime reacts with expansive clay in the presence of water and changes the physicochemical properties of expansive soil, which in turn alters the engineering properties of treated soil. Moreover, soil stabilisation and reinforcement using lime combined with agricultural and industrial waste by-products (e.g. fly ash, rice husk ash, recycled fibres) can extend the effectiveness of lime stabilised expansive soil.

This study presents an experimental investigation on the improvement of the geotechnical properties of expansive soil stabilised with bagasse fibre, bagasse ash combined without or with lime stabilisation. The agricultural waste by-products of bagasse ash and fibre, remained after crushing of sugar-cane for juice extraction, and the expansive soils, used in this investigation, were collected from Queensland, Australia. The stabilised soil specimens were prepared by changing the contents of bagasse ash from 0% to 25%, bagasse fibre from 0% to 2%, hydrated lime from 0% to 6.25%, and combined bagasse ash-hydrated lime from 0% to 25% by the dry mass of expansive soil. Several series of laboratory experiments have been performed on untreated and treated expansive soil samples with different additive contents and various curing times of 3, 7, 28, and 56 days. Another extensive microstructural analysis using scanning electron microscopy

(SEM), pH measurements, and Fourier transform infrared (FTIR) techniques has been carried out to evaluate the microstructure development of untreated and treated expansive soils. The outcomes of these experimental investigations showed that when the addition of bagasse ash into the expansive soils increased from 0% to 25%, the linear shrinkage reduced by 47%, the free swell potential decreased from approximately 10% to less than 0.5%, the swelling pressure reduction was from 80 kPa to 35 kPa (about 60%), the compressive strength at failure and the corresponding strain increased significantly by 48% and 40%. Meanwhile, the combination of bagasse ash and lime to stabilise soils when combined additive content increased up to 25% caused a significant increase in the compressive strength of 815% and the secant modulus of elasticity from 7.2 MPa to 107.2 MPa; reduced the linear shrinkage of 84% and the free swell potential down to less 0.5%; significantly decreased the swelling pressure from 80 kPa to around 10 kPa (88% reduction) and the compression indices from 0.484 to 0.083, just to name a few. It was noted that the improved geotechnical characteristics were more pronounced for lime treated soils with the combination of bagasse ash or fibre. The utilisation of bagasse ash or fibre for expansive soil stabilisation without or with lime combination not only effectively improved the geotechnical properties of expansive soil as curing time and additive content increased, but also assisted in minimising the adverse effects of agricultural waste by-products on the environment.

Numerical investigations based on the finite element method (FEM) incorporated in PLAXIS were carried out to evaluate a possible practical application of recycled fibre-lime reinforced soil as a replacement of geosynthetic reinforced traditional angular load transfer platform layer combined with columns or piles supported embankments founded on soft soils. An equivalent two-dimensional FEM model with proper modified parameters of structure and soil models has been adopted to investigate the performance of floating columns supported embankment reinforced without or with an FRLTP (fibre reinforced load transfer platform). Firstly, a series of numerical analysis was performed on the full geometry of columns supported embankment reinforced without or with an FRLTP of 0.5 m to examine the effectiveness of the FRLTP inclusion into the columns supported embankment system. The numerical results revealed that the embankment with FRLTP could effectively reduce the total and differential settlements, and the lateral

displacement of the embankment by 20%, 74% and 46%, respectively, when compared with the embankment without FRLTP. Subsequently, several series of extensive parametric studies on the influence of FRLTP properties, and the improvement depth ratios of soft soils, have been carried out to assess the behaviour of the columns supported embankment with FRLTP. The findings of the extensive parametric study indicated that the platform thickness has a significant influence on the embankment behaviour, especially in improving the total and differential settlements, the rigidity and stability of the embankment, and the more load transfer from the embankment to DCM columns. Meanwhile, Young's modulus of the FRLTP shows considerable effects on the differential settlement, the stress concentration ratio, but has a negligible effect on the lateral deformation of the investigated embankment. The improvement depth ratio reveals substantial impacts on the final settlement and the lateral deformation, but shows insignificant influence on the stress concentration ratio and the differential settlement during the embankment construction and post-construction time. The FRLTP shear strength parameters show significant influences on the stress concentration ratio and the differential settlement of the embankment. However, the enhancement in the embankment performance was more noticeable for the cohesion than the internal friction angle of the FRLTP.

ACKNOWLEDGEMENT

My PhD journey could not have been possible without the support provided by numerous people. Particularly, I would like to express my sincere appreciation and gratitude to my supervisors, family members and research colleagues.

Firstly, I would like to take this opportunity to express my deepest gratitude to my principal supervisor, A/Prof Hadi Khabbaz, and my co-supervisor, A/Prof Behzad Fatahi, for their continuous support associated with my research project, other aspects of my life, their guidance, time, patience, and leadership. Since the begin of my study, I have learnt many important things from them such as interpersonal and technical skills, critical thinking, presentation skills, and their knowledge and motivation encourage me to overcome many challenges and difficulties to achieve this milestone.

Secondly, I also gratefully thank all geotechnical research fellows who have been involved in my PhD study directly or indirectly. In particular, I would like to say thank you to supporting staff at UTS laboratories including Dr Lam Nguyen, Katie McBean, Md Johir, and my research colleagues Mr Harry Nguyen, Hayder Hassan and Thang Pham for either helping me complete the experimental program or giving me their valued advice.

In addition, I would like to sincerely acknowledge UTS Faculty of Engineering and Information Technology, and Centre of Built Infrastructure Research (CBIR) for their support and scholarships, which enable me to complete this PhD research. I also appreciate Ms Van Le for her kind support.

Finally yet importantly, I owe my immeasurable gratitude to my parents for their support always, their endless and unconditional love. I am also grateful to my brother and sister who always bring joys and happiness, motivate and encourage me to work hard and successfully achieve my goals.

LIST OF PUBLICATIONS

Conference Papers

1. Dang, L.C., Dang, C., Fatahi, B. & Khabbaz, H. 2016, 'Numerical Assessment of Fibre Inclusion in a Load Transfer Platform for Pile-Supported Embankments over Soft Soil', *Geo-China 2016*, eds D. Chen, J. Lee & W.J. Steyn, vol. GSP 266, ASCE, pp. 148-55.
2. Dang, L.C., Hasan, H., Fatahi, B., Jones, R. & Khabbaz, H. 2015, 'Effects of Bagasse Ash and Hydrated Lime Addition on Engineering Properties of Expansive Soil', *Fifth International Conference on Geotechnique, Construction Materials and Environment (GEOMATE 2015)*, Osaka, Japan, pp. 90-5.
3. Dang, L., Hasan, H., Fatahi, B. & Khabbaz, H. 2015b, 'Influence of Bagasse Ash and Hydrated Lime on Strength and Mechanical Behaviour of Stabilised Expansive Soil', *the 68th Canadian Geotechnical Conference and the 7th Canadian Permafrost Conference (GEOQuébec 2015)*, eds J. Côté & M. Allard, the Canadian Geotechnical Society (CGS), Québec City, Canada, pp. 1-8.
4. Dang, L.C., Dang, C.C. & Khabbaz, H. 2017a, 'Behaviour of Columns and Fibre Reinforced Load Transfer Platform Supported Embankments Built on Soft Soil', *the 15th International Conference of the International Association for Computer Methods and Advances in Geomechanics*, Wuhan, China.
5. Dang, L.C. & Khabbaz, H. 2018a, 'Assessment of the Geotechnical and Microstructural Characteristics of Lime Stabilised Expansive Soil with Bagasse Ash', *the 71st Canadian Geotechnical Conference and the 13th Joint CGS/IAH-CNC Groundwater Conference (GeoEdmonton 2018)*, the Canadian Geotechnical Society (CGS), Alberta, Canada.
6. Dang, L.C. & Khabbaz, H. 2018b, 'Enhancing the Strength Characteristics of Expansive Soil Using Bagasse Fibre', in W. Wu & H.-S. Yu (eds), *Proceedings of China-Europe Conference on Geotechnical Engineering. Springer Series in Geomechanics and Geoengineering*, Springer, Cham, pp. 792-6.

7. Dang, L.C. & Khabbaz, H. 2018c, 'Shear Strength Behaviour of Bagasse Fibre Reinforced Expansive Soil', *IACGE2018*, vol. Geotechnical Special Publications, ASCE, Chongqing, China.
8. Dang, L.C., Khabbaz, H. & Fatahi, B. 2017b, 'Evaluation of Swelling Behaviour and Soil Water Characteristic Curve of Bagasse Fibre and Lime Stabilised Expansive Soil', *PanAm-UNSAT 2017*, vol. GSP 303, ASCE, Texas, USA, pp. 58-70.
9. Dang, L.C., Khabbaz, H. & Fatahi, B. 2017c, 'An Experimental Study on Engineering Behaviour of Lime and Bagasse Fibre Reinforced Expansive Soils', *19th International Conference on Soil Mechanics and Geotechnical Engineering (19th ICSMGE)*, ISSMGE, Seoul, Republic of Korea, pp. 2497-500.
10. Hasan, H., Dang, L., Khabbaz, H. & Fatahi, B. 2017, 'Swelling Pressure and Consolidation of Soft Clay Stabilized With Bagasse Ash and Lime', in I.A.-Q. Andreas Loizos, Tom Scarpas (ed.), *Bearing Capacity of Roads, Railways and Airfields*, CRC Press, London, UK pp. 1069-75.

Book Chapters

11. Dang, L.C., Dang, C.C. & Khabbaz, H. 2018a, 'Numerical Analysis on the Performance of Fibre Reinforced Load Transfer Platform and Deep Mixing Columns Supported Embankments', in M. Bouassida & M.A. Meguid (eds), *Ground Improvement and Earth Structures*, Springer, Cham, pp. 157-69.
12. Dang, L.C., Dang, C.C. & Khabbaz, H. 2018b, 'A Parametric Study of Deep Mixing Columns and Fibre Reinforced Load Transfer Platform Supported Embankments', in H. Khabbaz, H. Youn & M. Bouassida (eds), *New Prospects in Geotechnical Engineering Aspects of Civil Infrastructures*, Springer, Cham, pp. 179-94.
13. Dang, L.C. & Khabbaz, H. 2019, 'Experimental Investigation on the Compaction and Compressible Properties of Expansive Soil Reinforced with Bagasse Fibre and Lime', in J.S. McCartney & L.R. Hoyos (eds), *Recent Advancements on Expansive Soils*, Springer, Cham, pp. 64-78.

Journal Papers

- 14.Dang, L.C., Fatahi, B. & Khabbaz, H. 2016a, 'Behaviour of Expansive Soils Stabilized with Hydrated Lime and Bagasse Fibres', *Procedia Engineering*, vol. 143, pp. 658-65.
- 15.Dang, L.C., Hasan, H., Fatahi, B., Jones, R. & Khabbaz, H. 2016b, 'Enhancing the Engineering Properties of Expansive Soil Using Bagasse Ash and Hydrated Lime', *International Journal of GEOMATE*, vol. 11, no. 25, pp. 2447-54.
- 16.Hasan, H., Dang, L., Khabbaz, H., Fatahi, B. & Terzaghi, S. 2016, 'Remediation of Expansive Soils Using Agricultural Waste Bagasse Ash', *Procedia Engineering*, vol. 143, pp. 1368-75.
- 17.Dang, L.C., Dang, C.C. & Khabbaz, H., 'Modelling of Columns and Fibre Reinforced Load Transfer Platform Supported Embankments', *Proceedings of the Institution of Civil Engineers - Ground Improvement*. doi.org/10.1680/jgrim.18.00039
- 18.Dang, L.C., Dang, C.C. & Khabbaz, H., 'Numerical Investigation on the Effect of Columns and Fibre Reinforced Load Transfer Platform Supported Embankments', (*submitted*).
- 19.Dang, L.C., Khabbaz, H. & Hasan, H., 'Geotechnical Characteristics of Expansive Soils Stabilised with Bagasse Ash and Hydrated Lime', (*submitted*).
- 20.Dang, L.C. & Khabbaz, H., 'Assessment of the Engineering Characteristics of Lime Treated Expansive Soil with Bagasse Fibre', (*in preparation*).

TABLE OF CONTENTS

ABSTRACT	iii
ACKNOWLEDGEMENT	vi
LIST OF PUBLICATIONS.....	vii
TABLE OF CONTENTS.....	x
LIST OF FIGURES	xiv
LIST OF TABLES	xxiv
CHAPTER 1: INTRODUCTION.....	1
1.1. OVERVIEW	1
1.2. STATEMENT OF PROBLEM	7
1.3. RESEARCH OBJECTIVES AND SCOPE	9
1.4. THESIS ORGANISATION	15
CHAPTER 2: LITERATURE REVIEW.....	18
2.1. INTRODUCTION.....	18
2.2. CHEMICAL AND MECHANICAL SOIL STABILISATION METHOD	20
2.2.1. Lime Stabilisation	21
2.2.2. Cement Stabilisation	22
2.2.3. Agricultural and Industrial By-products Used for Construction and Soil Stabilisation	24
2.2.4. Behaviour of Cement, Lime Treated Expansive Soil with Agricultural and Industrial By-products	33
2.2.5. Behaviour of Fibre Reinforcement of Expansive Soil without or with Cement, Lime Treatment.....	51
2.3. SUMMARY AND GAP IDENTIFICATION.....	72
CHAPTER 3: MATERIALS, SAMPLE PREPARATION AND LABORATORY TESTING PROGRAM.....	79
3.1. INTRODUCTION	79
3.2. MATERIALS	79

3.2.1. Natural Expansive Soil	79
3.2.1. Bagasse Ash.....	83
3.2.2. Bagasse Fibre.....	85
3.2.3. Hydrated Lime	86
3.3. EXPERIMENTAL METHODS	88
3.3.1. Mixing of Materials	88
3.3.2. pH Test.....	90
3.3.3. Linear Shrinkage.....	91
3.3.4. Standard Compaction Test.....	92
3.3.5. Unconfined Compression Test	94
3.3.6. Indirect Tensile Strength Test.....	97
3.3.7. California Bearing Ratio Test	99
3.3.8. Swell Potential Test	101
3.3.9. One-dimensional (1D) Swelling Pressure and Consolidation Tests.....	102
3.3.10. Triaxial Shear Test.....	104
3.3.11. Microstructural Analysis.....	107
3.3.12. Filter Paper Method	109
3.4. SUMMARY	112
CHAPTER 4: GEOTECHNICAL CHARACTERISTICS OF EXPANSIVE SOIL STABILISED WITH BAGASSE ASH AND HYDRATED LIME	113
4.1. INTRODUCTION.....	113
4.2. EXPERIMENTAL RESULTS AND DISCUSSION.....	114
4.2.1. Determination of Optimum Lime Content for Lime Soil Mixtures.....	114
4.2.2. Influence of Additive Content on Compaction Characteristics	116
4.2.3. Influence of Additive Content on Stress-Strain Behaviour	119
4.2.4. Influence of Additive Content on UCS Values	122
4.2.5. Influence of Curing Time on Unconfined Compressive Strength	126
4.2.6. Influence of Additive Content on California Bearing Ratio.....	131
4.2.7. Influence of Additive Content on Linear Shrinkage.....	134
4.2.8. Influence of Additive Content on Time-Dependent Swelling.....	137
4.2.9. Influence of Additive Content on Swell Potential	141

4.2.10. Influence of Additive Content on Swelling Pressure.....	144
4.2.11. Influence of Bagasse Ash and Lime on Secant Modulus	146
4.2.12. Influence of Bagasse Ash and Lime on Compression Characteristics	151
4.2.13. Influence of Bagasse Ash and Lime on Microstructural Evolution.....	153
4.3. SUMMARY	158
CHAPTER 5: ENHANCING GEOTECHNICAL PROPERTIES OF EXPANSIVE SOIL USING RANDOMLY DISTRIBUTED BAGASSE FIBRE AND HYDRATED LIME	163
5.1. INTRODUCTION	163
5.2. EXPERIMENTAL RESULTS AND DISCUSSION	164
5.2.1. Effect of Bagasse Fibre and Lime Content on Compaction Characteristics	164
5.2.2. Effect of Bagasse Fibre and Lime Content on Linear Shrinkage	166
5.2.3. Effect of Bagasse Fibre and Lime on Stress-Strain Behaviour	169
5.2.4. Effect of Bagasse Fibre Reinforcement on the Failure Characteristics	174
5.2.5. Effect of Bagasse Fibre Reinforcement and Lime on UCS Values.....	175
5.2.6. Effect of Bagasse Fibre Reinforcement on Brittleness Index (I_B)	177
5.2.7. Effect of Lime and Bagasse Fibre on Indirect Tensile Strength.....	179
5.2.8. Effect of Bagasse Fibre and Lime on California Bearing Ratio	184
5.2.9. Effect of Bagasse Fibre and Lime on the Swell Potential	186
5.2.10. Effect of Bagasse Fibre and Lime on Swelling Pressure.....	190
5.2.11. Effect of Bagasse Fibre and Lime on the Compression Characteristics....	192
5.2.12. Effect of Bagasse Fibre and Lime on Soil-Water Characteristic Curves ..	197
5.2.13. Effect of Bagasse Fibre Reinforcement on the Shear Strength characteristics	201
5.2.14. Microstructure Analysis.....	212
5.3. SUMMARY	216
CHAPTER 6: NUMERICAL ANALYSIS ON THE PERFORMANCE OF FIBRE REINFORCED LOAD TRANSFER PLATFORM AND COLUMNS SUPPORTED EMBANKMENTS	222
6.1. INTRODUCTION	222
6.2. CASE STUDY 1	230

6.2.1. NUMERICAL MODELING	234
6.2.2. ANALYSIS OF RESULTS AND DISCUSSION	239
6.3. CASE STUDY 2	245
6.3.1. NUMERICAL MODELING	249
6.3.2. ANALYSIS OF RESULTS AND DISCUSSION	254
6.4. CASE STUDY 3	291
6.4.1. NUMERICAL MODELING	293
6.4.2. ANALYSIS OF RESULTS AND DISCUSSION	296
6.5. SUMMARY	299
CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS.....	302
7.1. SUMMARY	302
7.2. CONCLUSIONS	307
7.2.1. Application of Bagasse Ash and Lime Treated Expansive Soil	307
7.2.2. Application of Lime and Bagasse Fibre Reinforced Expansive Soil.....	310
7.2.3. Numerical Simulations on the Behaviour of FRLTP and Columns Supported Embankments.....	316
7.3. RECOMMENDATIONS FOR FUTURE INVESTIGATIONS.....	317
REFERENCES.....	320

LIST OF FIGURES

<i>Figure 1.1 Structural damage due to ground heaving after (Al-Rawas et al. 2005)</i>	<i>3</i>
<i>Figure 1.2 A cracked road in Adelaide, Australia after (Considine 1984)</i>	<i>4</i>
<i>Figure 2.1 Stress-strain behaviour of lime treated expansive soil at 28 days curing after (Sharma et al. 2008).....</i>	<i>34</i>
<i>Figure 2.2 Effect of rice husk ash on UCS values of lime treated expansive soil at 28 days curing after (Sharma et al. 2008).....</i>	<i>37</i>
<i>Figure 2.3 Effect of lime content and curing time on the UCS of expansive soil after (Bell 1996)</i>	<i>38</i>
<i>Figure 2.4 Effect of lime content and curing time on the UCS of clayed soil after (Bell 1996)</i>	<i>38</i>
<i>Figure 2.5 Effect of fly ash content and curing time on the UCS of lime treated expansive clay after (Zha et al. 2008).....</i>	<i>39</i>
<i>Figure 2.6 Variation of pH values of gypseous soil with curing time and additive content after (Aldaoood et al. 2014b)</i>	<i>41</i>
<i>Figure 2.7 Relationship between pH values and curing ages with different amount of sludge ash-cement combination after (Chen & Lin 2009)</i>	<i>42</i>
<i>Figure 2.8 Variation of pH with the amount and types of additive after (Solanki et al. 2009)</i>	<i>43</i>
<i>Figure 2.9 Effect of fly ash (FA), bagasse ash (BA) content and curing time on the CBR of treated clayey soil after (Anupam et al. 2013).....</i>	<i>44</i>
<i>Figure 2.10 Effect of lime content on the linear shrinkage of montmorillonite clay soil after (Bell 1996)</i>	<i>45</i>
<i>Figure 2.11 Variation of axial shrinkage of expansive soil mixed with various percentages of fly ash-lime after (Zha et al. 2008)</i>	<i>46</i>
<i>Figure 2.12 Effect of lime and cement on swell potential after (Phanikumar et al. 2014)</i>	<i>48</i>
<i>Figure 2.13 Effect of lime and fly ash on swelling pressure after (Phanikumar 2009) ..</i>	<i>49</i>
<i>Figure 2.14 Variation of swelling pressure of expansive soil mixed with various percentages of fly ash-lime without curing after (Zha et al. 2008).....</i>	<i>50</i>

<i>Figure 2.15 Variation of swelling pressure of expansive soil mixed with various percentages of fly ash-lime with curing for 7 days after (Zha et al. 2008).....</i>	<i>50</i>
<i>Figure 2.16 Influence of fibre contents and compaction moisture contents on the volumetric shrinkage strain of soils reinforced with carbon fibre after (Bhadriraju et al. 2005)</i>	<i>52</i>
<i>Figure 2.17 Influence of fibre types on the volumetric shrinkage strain of soils with fibre reinforcement after (Bhadriraju et al. 2005)</i>	<i>53</i>
<i>Figure 2.18 Effect of fibre length on the volumetric shrinkage strain: (a) coir pith fibre content; (b) short coir fibre content after (Jayasree et al. 2015)</i>	<i>53</i>
<i>Figure 2.19 Effect of fibre contents and aspect ratios on the compressive strength of treated soils with strips waste plastic fibre reinforcement after (Ahmed et al. 2011)</i>	<i>54</i>
<i>Figure 2.20 Effect of fibre inclusion on the unconfined compressive strength and the indirect tensile strength of 12% rice husk ash+12% lime treated soils reinforced with waste plastic fibres after (Muntohar et al. 2013).....</i>	<i>55</i>
<i>Figure 2.21 Effect of fibre contents and curing time on the compressive strength of cement treated clayey soils with natural fibre reinforcement: (a) Pinus Roxburghii fibres; (b) Grewia Optivia fibres after (Sharma et al. 2005)</i>	<i>57</i>
<i>Figure 2.22 Effect of fibre contents and aspect ratios on the indirect tensile strength of treated soils with strips waste plastic fibre reinforcement after (Ahmed et al. 2011)</i>	<i>58</i>
<i>Figure 2.23 Effect of fibre contents on the ratio of indirect tensile strength and compressive strength after (Ahmed et al. 2011).....</i>	<i>59</i>
<i>Figure 2.24 Effect of fibre contents on the indirect tensile strength of combined rice husk ash-pond ash stabilised soils reinforced with polypropylene fibres at 4% cement treatment after (Kumar & Gupta 2016)</i>	<i>60</i>
<i>Figure 2.25 Effect of fibre contents on soaked CBR of 12% rice husk ash+12% lime treated soils with waste plastic fibre reinforcement after (Muntohar et al. 2013)</i>	<i>61</i>
<i>Figure 2.26 Correlation between secant modulus of elasticity and soaked CBR with fibre contents after (Muntohar et al. 2013)</i>	<i>62</i>
<i>Figure 2.27 Effect of fibre contents on the free swelling strain of expansive soil reinforced with fibre after (Estabragh et al. 2014)</i>	<i>63</i>

<i>Figure 2.28 Effect of fibre length and diameter on the free swell potential of soil treated with 1.5% fibre content after (Estabragh et al. 2014)</i>	<i>64</i>
<i>Figure 2.29 Effect of fibre contents on the swelling potential of expansive soil reinforced with hay fibre inclusion after (Mohamed 2013).....</i>	<i>64</i>
<i>Figure 2.30 Effect of fibre contents on the swelling pressure of expansive soil reinforced with fibre after (Estabragh et al. 2014)</i>	<i>66</i>
<i>Figure 2.31 Effect of fibre length and fibre contents on the swelling pressure of soil treated with fibre width of 0.30 mm after (Estabragh et al. 2014)</i>	<i>66</i>
<i>Figure 2.32 Soil water characteristic curves of untreated soils (A or D) and different types of fly ash (F1, F2) or bottom ash (B) treated expansive soils reinforced with polypropylene fibres (P) after (Puppala et al. 2006)</i>	<i>70</i>
<i>Figure 2.33 Soil water characteristic curves of untreated soil and expansive soils reinforced with polypropylene fibres after (Malekzadeh & Bilsel 2014)</i>	<i>71</i>
<i>Figure 3.1 Air-dried expansive soil</i>	<i>81</i>
<i>Figure 3.2 Particle size distribution curve for natural expansive soil</i>	<i>82</i>
<i>Figure 3.3 Selected expansive soil with particles smaller 2.36mm</i>	<i>82</i>
<i>Figure 3.4 Sugar-cane bagasse ash</i>	<i>83</i>
<i>Figure 3.5 Scanning electron microscopy (SEM) image of sugar-cane bagasse ash.....</i>	<i>84</i>
<i>Figure 3.6 Selected sugar-cane bagasse ash employed in this study</i>	<i>84</i>
<i>Figure 3.7 Bagasse fibre used in this investigation</i>	<i>86</i>
<i>Figure 3.8 Hydrated lime</i>	<i>87</i>
<i>Figure 3.9 Additive-soil mixing.....</i>	<i>88</i>
<i>Figure 3.10 pH meter and the probe.....</i>	<i>91</i>
<i>Figure 3.11 Linear shrinkage of (a) untreated soils and (b) 6% lime treated soils with 2% bagasse fibre</i>	<i>92</i>
<i>Figure 3.12 Standard compaction test: (a) compaction tools; (b) compacted soil sample</i>	<i>94</i>
<i>Figure 3.13 Unconfined compressive strength test: (a) a typical UCS mould; (b) selected soil samples prepared and sealed in vinyl plastic wrap for curing</i>	<i>96</i>
<i>Figure 3.14 Conventional compression testing machine</i>	<i>96</i>
<i>Figure 3.15 Indirect tensile strength test (known as Brazilian or splitting test)</i>	<i>98</i>

<i>Figure 3.16 A selected soil sample after completion of the indirect tensile strength test</i>	98
<i>Figure 3.17 CBR samples under curing condition</i>	100
<i>Figure 3.18 CBR samples under soaking condition</i>	100
<i>Figure 3.19 Selected samples after completion of CBR tests</i>	101
<i>Figure 3.20 Swell potential test setup</i>	102
<i>Figure 3.21 One-dimensional (1D) consolidation test (Oedometer test)</i>	104
<i>Figure 3.22 Triaxial compression test</i>	106
<i>Figure 3.23 A selected sample after completion of triaxial shear test</i>	107
<i>Figure 3.24 Scanning electron microscope (SEM) test</i>	108
<i>Figure 3.25 Fourier transform infrared (FTIR) test</i>	109
<i>Figure 3.26 Soil suction test: (a) sample preparation and tools; (b) and (c) placement of soil samples in a well-insulated container for suction equilibrium</i>	111
<i>Figure 4.1 pH values of lime and bagasse ash-lime (BA+L) stabilised expansive soil after 1 hour of mixing</i>	116
<i>Figure 4.2 Compaction curve of natural expansive soil</i>	117
<i>Figure 4.3 Influence of (a) bagasse ash and lime-bagasse ash, (b) hydrated lime content on the maximum dry density of treated expansive soil</i>	118
<i>Figure 4.4 Influence of different bagasse ash content on stress-strain behaviour of expansive soil</i>	120
<i>Figure 4.5 Influence of different hydrated lime-bagasse ash content on stress-strain behaviour of expansive soil after 28 days of curing</i>	122
<i>Figure 4.6 Influence of bagasse ash addition on average UCS value of treated expansive soil with various curing times</i>	123
<i>Figure 4.7 Influence of hydrated lime addition on average UCS value of treated expansive soil with various curing times</i>	124
<i>Figure 4.8 Influence of hydrated lime and bagasse ash admixtures on average UCS value of treated expansive soil with various curing times</i>	125
<i>Figure 4.9 Influence of curing time on unconfined compressive strength of treated expansive soil with various bagasse ash contents</i>	128

<i>Figure 4.10 Influence of curing time on unconfined compressive strength of treated expansive soil with various hydrated lime contents</i>	<i>128</i>
<i>Figure 4.11 Influence of curing time on unconfined compressive strength of treated expansive soil with various hydrated lime-bagasse ash contents</i>	<i>130</i>
<i>Figure 4.12 Influence of longer curing time on unconfined compressive strength of treated expansive soil with various hydrated lime and lime-bagasse ash contents</i>	<i>131</i>
<i>Figure 4.13 Influence of bagasse ash admixtures on average unsoaked CBR of treated expansive soil with various curing times</i>	<i>132</i>
<i>Figure 4.14 Influence of hydrated lime, combined hydrated lime-bagasse ash admixtures on unsoaked CBR of treated expansive soil after curing for 28 days</i>	<i>134</i>
<i>Figure 4.15 Linear shrinkage of expansive soil mixed with various bagasse ash contents for different curing times.....</i>	<i>136</i>
<i>Figure 4.16 Linear shrinkage of hydrated lime treated expansive soil with different additive contents and curing times.....</i>	<i>136</i>
<i>Figure 4.17 Linear shrinkage of hydrated lime-bagasse ash treated expansive soil with different additive contents and curing times</i>	<i>137</i>
<i>Figure 4.18 Influence of bagasse ash on swelling strain with time of expansive soil ..</i>	<i>138</i>
<i>Figure 4.19 Influence of hydrated lime on swelling strain with time of expansive soil</i>	<i>138</i>
<i>Figure 4.20 Influence of hydrated lime-bagasse ash combination on swelling strain with time of expansive soil</i>	<i>141</i>
<i>Figure 4.21 Influence of bagasse ash and hydrated lime-bagasse ash additions on the free swell potential of treated expansive soil</i>	<i>142</i>
<i>Figure 4.22 Influence of hydrated lime only and hydrated lime-bagasse ash additions on the free swell potential of treated expansive soil</i>	<i>143</i>
<i>Figure 4.23 Influence of bagasse ash and hydrated lime-bagasse ash additions on the swelling pressure of treated expansive soil.....</i>	<i>145</i>
<i>Figure 4.24 Influence of hydrated lime alone and hydrated lime-bagasse ash additions on the swelling pressure of treated expansive soil.....</i>	<i>146</i>
<i>Figure 4.25 Influence of bagasse ash additions on Young's modulus of treated expansive soil with different curing times.....</i>	<i>147</i>

<i>Figure 4.26 Influence of hydrated lime additions on Young's modulus of treated expansive soil with different curing times.....</i>	<i>149</i>
<i>Figure 4.27 Influence of hydrated lime-bagasse ash additions on Young's modulus of treated expansive soil with different curing times.....</i>	<i>150</i>
<i>Figure 4.28 Influence of hydrated lime-bagasse ash addition on compression curves of treated expansive soil after 7 days of curing</i>	<i>152</i>
<i>Figure 4.29 Influence of hydrated lime-bagasse ash addition on compression index of treated expansive soil for effective stress ranging from 400 kPa to 600 kPa</i>	<i>153</i>
<i>Figure 4.30 Fourier transform infrared (FTIR) spectra of untreated soil and hydrated lime, lime-bagasse ash treated soil after 28 days of curing.....</i>	<i>155</i>
<i>Figure 4.31 SEM images of (a) untreated expansive soil and expansive soil treated with (b) 6.25% hydrated lime and (c) 25% BA+Lime after 28 days of curing.....</i>	<i>158</i>
<i>Figure 5.1 Compaction curves of (a) natural expansive soil and (b) expansive soil reinforced with different bagasse fibre and hydrated lime contents.....</i>	<i>166</i>
<i>Figure 5.2 Linear shrinkage of expansive soil mixed with various bagasse fibre contents along with different curing periods.....</i>	<i>168</i>
<i>Figure 5.3 Linear shrinkage of expansive soil mixed with various contents of bagasse fibres-lime combination after 7 days of curing</i>	<i>168</i>
<i>Figure 5.4 Axial stress-strain relationship of expansive soil reinforced with different bagasse fibre contents</i>	<i>170</i>
<i>Figure 5.5 Variations of the unconfined compressive strength and secant modulus of expensive soil reinforced with different bagasse fibre contents</i>	<i>171</i>
<i>Figure 5.6 Stress-strain behaviour for untreated soil and bagasse fibre reinforced soils with (a) 4% lime and (b) 6% lime after 28 days of curing.....</i>	<i>173</i>
<i>Figure 5.7 Effect of bagasse fibre (BF) addition on failure characteristics of 4% lime treated soils with: (a) 0% BF; (b) 0.5% BF; (c) 1% BF and (d) 2% BF.....</i>	<i>175</i>
<i>Figure 5.8 Effect of bagasse fibre addition on average UCS values of treated expansive soil with various curing times</i>	<i>176</i>
<i>Figure 5.9 Variation of UCS values for 4% lime and 6% lime treated expansive soils with bagasse fibre reinforcement after 28 days of curing</i>	<i>177</i>

<i>Figure 5.10 Effect of bagasse fibre reinforcement on brittleness index (I_B) of lime treated expansive soil after 28 days of curing.....</i>	<i>179</i>
<i>Figure 5.11 Tensile load-displacement curves for untreated soil and bagasse fibre reinforced soils with (a) 4% lime and (b) 6% lime after 28 days of curing.....</i>	<i>181</i>
<i>Figure 5.12 Effect of bagasse fibre content on the tensile strength of lime treated soil</i>	<i>183</i>
<i>Figure 5.13 Variation of the soaked CBR of randomly distributed bagasse fibre reinforced expansive soil after 7 days of curing</i>	<i>184</i>
<i>Figure 5.14 Variation of the soaked CBR of randomly distributed bagasse fibre and lime reinforced expansive soil after a curing period of 7 days.....</i>	<i>186</i>
<i>Figure 5.15 Variation of swell potential of randomly distributed bagasse fibre reinforced expansive soil</i>	<i>187</i>
<i>Figure 5.16 Variation of swell potential of various percentages of randomly distributed bagasse fibre and lime reinforced expansive soil (from CBR tests)</i>	<i>188</i>
<i>Figure 5.17 Variation of free swell potential of various percentages of randomly distributed bagasse fibre and lime reinforced expansive soil (from Oedometer tests).</i>	<i>190</i>
<i>Figure 5.18 Variation of swelling pressure of various percentages of randomly distributed bagasse fibre (BF) and lime (L) reinforced expansive soil</i>	<i>191</i>
<i>Figure 5.19 Variation of effective stress-void ratio curves of 0.5% randomly distributed bagasse fibre and various contents of lime reinforced expansive soil.....</i>	<i>193</i>
<i>Figure 5.20 Variation of effective stress-void ratio curves of various content of randomly distributed bagasse fibre and 2.5% lime reinforced expansive soil</i>	<i>194</i>
<i>Figure 5.21 Variation of preconsolidation pressure of expansive soil reinforced with various contents of bagasse fibre and 2.5% lime.....</i>	<i>195</i>
<i>Figure 5.22 Variation of compression and swelling indices of expansive soil reinforced with various contents of bagasse fibre and 2.5% lime.....</i>	<i>196</i>
<i>Figure 5.23 Variation of soil-water characteristic curves of various percentages of randomly distributed bagasse fibre and lime reinforced expansive soil as a function of (a) degree of saturation; (b) gravimetric water content.....</i>	<i>200</i>

<i>Figure 5.24 Deviatoric stress-axial strain behaviour of expansive soil reinforced with bagasse fibre at different confining pressures of (a) 50 kPa, (b) 100 kPa and (c) 200kPa</i>	204
<i>Figure 5.25. Excess pore water pressure change of expansive soil reinforced with bagasse fibre at different confining pressures of (a) 50 kPa, (b) 100 kPa and (c) 200kPa</i>	207
<i>Figure 5.26. Variation of ultimate deviatoric strength of expansive soil reinforced with different bagasse fibre contents at confining pressures of 50, 100 and 200 kPa</i>	208
<i>Figure 5.27. Peak strength envelope of expansive soil reinforced with different bagasse fibre contents</i>	209
<i>Figure 5.28. Variation of shear strength parameters with bagasse fibre content, (a) internal friction angle and (b) cohesion</i>	211
<i>Figure 5.29 SEM image of interaction and interlocking mechanism between bagasse fibre surface and soil matrix</i>	212
<i>Figure 5.30 SEM images of (a) untreated expansive soil, (b) 6% lime treated soil, and (c, d) 6% lime treated soils with 1% bagasse fibre after 28 days of curing</i>	215
<i>Figure 6.1 Cross section of the fibre reinforced load transfer platform and DCM columns supported embankment (Case study 1)</i>	231
<i>Figure 6.2 Mesh and boundary conditions for a 2D FEM analysis of embankment</i>	236
<i>Figure 6.3 Comparison between field measurement and 2D numerical prediction: (a) settlement with time; (b) excess pore water pressure with time</i>	238
<i>Figure 6.4 Development of settlement and excess pore water pressure with time</i>	240
<i>Figure 6.5 Development of (a) vertical effective stress on the top of DCM columns and (b) stress concentration ratio with time</i>	242
<i>Figure 6.6 Variation of surface settlement versus horizontal distance from centerline</i>	243
<i>Figure 6.7 Development of settlement with depth for different embankment heights of H=2, 3 & 4m</i>	245
<i>Figure 6.8 Cross-section of the FRLTP and DCM columns supported embankment (Case study 2)</i>	246
<i>Figure 6.9 Mesh and boundary conditions for a 2D FEM analysis of embankment</i>	252

<i>Figure 6.10 Comparison between field measurements, 2D and 3D numerical predictions of the embankment settlement at (a) ground surface and (b) column top with time</i>	<i>254</i>
<i>Figure 6.11 Development of (a) total settlement with time and (b) total settlement at embankment construction completion and 2 years post-construction for different improvement depth ratios (β)</i>	<i>256</i>
<i>Figure 6.12 Variation of differential settlement versus embankment height for different improvement depth ratios (β)</i>	<i>259</i>
<i>Figure 6.13 Effective principle stresses of the embankment with FRLTP at the construction end for the improvement depth ratios of (a) $\beta=0.5$ and (b) $\beta=0.83$</i>	<i>259</i>
<i>Figure 6.14 Variation of SCR with embankment height for different improvement depth ratios (β)</i>	<i>262</i>
<i>Figure 6.15 Variation of lateral displacement with depth for different improvement depth ratios (β) at (a) completion of embankment construction and (b) 2 years post-construction</i>	<i>265</i>
<i>Figure 6.16 Variation of lateral displacement of the embankment toe for different improvement depth ratio at embankment construction completion and 2 years post-construction</i>	<i>265</i>
<i>Figure 6.17 Variation of total settlement with time for different FRLTP thickness</i>	<i>267</i>
<i>Figure 6.18 Variation of differential settlement with embankment height for various FRLTP thickness</i>	<i>269</i>
<i>Figure 6.19 Variation of SCR with embankment height for various FRLTP thickness</i>	<i>271</i>
<i>Figure 6.20 Variation of lateral displacement with depth for various FRLTP thickness at 2 years post-construction</i>	<i>273</i>
<i>Figure 6.21 Effect of FRLTP Young's modulus variation on stress concentration ratio</i>	<i>275</i>
<i>Figure 6.22 Effect of FRLTP Young's modulus on differential settlement</i>	<i>276</i>
<i>Figure 6.23 Variation of the lateral displacement with depth for various elastic deformation modulus of FRLTP at 2 years post-construction</i>	<i>278</i>
<i>Figure 6.24 Effect of the FRLTP cohesion on stress concentration ratio</i>	<i>280</i>
<i>Figure 6.25 Effect of FRLTP cohesion on differential settlement</i>	<i>281</i>

<i>Figure 6.26 Variation of the lateral displacement with depth for various cohesion values of FRLTP at 2 years post-construction</i>	<i>282</i>
<i>Figure 6.27 Effect of FRLTP friction angle on stress concentration ratio</i>	<i>284</i>
<i>Figure 6.28 Effect of FRLTP friction angle on differential settlement</i>	<i>285</i>
<i>Figure 6.29 Variation of the lateral displacement with depth for various friction angles of FRLTP at 2 years of post-construction</i>	<i>286</i>
<i>Figure 6.30 Effect of the FRLTP tensile strength (STS) on stress concentration ratio</i>	<i>288</i>
<i>Figure 6.31 Effect of the FRLTP tensile strength (STS) on differential settlement</i>	<i>288</i>
<i>Figure 6.32 Variation of lateral displacement with depth for various FRLTP tensile strength (STS) at 2 years of post-construction</i>	<i>290</i>
<i>Figure 6.33 Cross-section of the FRLTP and piles supported embankment (case study 3)</i>	<i>292</i>
<i>Figure 6.34 2D Model adopted for analysis of embankment</i>	<i>292</i>
<i>Figure 6.35 Earth pressure acting on soil surface between piles</i>	<i>297</i>
<i>Figure 6.36 Earth pressure acting on the top of reinforced concrete</i>	<i>297</i>
<i>Figure 6.37 Comparison between measured and computed excess pore water pressure</i>	<i>299</i>

LIST OF TABLES

Table 2.1 Chemical compositions of fly ash and bottom ash after (Çokça 2001; Fatahi & Khabbaz 2013; Punthutaecha et al. 2006).....	28
Table 2.2 Chemical compositions of sugar-cane bagasse ash after (Alavéz-Ramírez et al. 2012; Anupam et al. 2013; Bahurudeen et al. 2014; Bahurudeen & Santhanam 2014; Chusilp et al. 2009a; Osinubi et al. 2009a)	30
Table 3.1 Physical and mechanical characteristics of natural soil	80
Table 3.2. Chemical composition of natural soil	81
Table 3.3. Physical and chemical characteristics of sugar-cane bagasse ash.....	85
Table 3.4. Chemical composition and physical properties of hydrated lime	87
Table 3.5. Summary of mixes used in this study	89
Table 4.1 A number of tested specimens	115
Table 5.1. Variation of air entry values of natural soil and bagasse fibre-lime stabilised soils	201
Table 6.1 Material properties of the embankment and subgrade soil layers.....	232
Table 6.2. Construction stages adopted in the FEM simulation procedure	233
Table 6.3. Material properties of subgrade soil layers used in Modified Cam Clay model	248
Table 6.4. Material properties of the embankment, FRLTP, DCM columns and sandy clay strata adopted in Mohr-Coulomb model	248
Table 6.5. Construction stages in the FEM simulation of embankment construction procedure.....	249
Table 6.6 Material properties for Mohr-Coulomb Model used in the FEM simulation (after Liu et al. 2007; Anggraini et al. 2015)	293
Table 6.7 Material properties for Modified Cam Clay model used in the FEM simulation (after Liu et al. 2007)	294