

DEFORMATION BEHAVIOUR OF SOFT GROUND TREATED WITH A
GROUP OF BOTTOM ASH COLUMNS

MOHAMAD HAFEEZI BIN ABDULLAH

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

School of Civil Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

AUGUST 2022

DEDICATION

To my lovely parents, who gave me endless support and prayers,

To my siblings, for their understanding and support,

To my beloved wife, for her patience and sacrifice,

To all my friends who were here together in this journey.

ACKNOWLEDGEMENT

In the name of Allah, the Most Gracious, the Most Compassionate. May the peace and blessings of Allah be upon Prophet Muhammad (SAW), his family, companions and those who follow his guidance until the Day of Ressurrection (Ameen).

My profound gratitude goes to my main supervisor Assoc. Prof. Ir. Ts. Dr Ahmad Safuan A. Rashid for his guidance, patience and support throughout the execution of this research. I wish to thank my co-supervisors, Ts. Dr Nor Zurairahetty, Prof. Dr Aminaton Marto and Dr Ng Kok Shien for their mentorship, guidance and encouragement in this journey. Their endless support has been greatly appreciated. I also appreciate all my colleagues and technical staff of the Geotechnical Engineering laboratory for their assistance during the research.

Acknowledgement is due to the Yayasan Biasiswa Tunku Abdul Rahman Sarawak (YBSTAR) for their financial support and sponsorship of this research. My appreciation goes to my loving parents Abdullah Hassan and Rokayah Muhamad as well as my siblings Mohamad Hanif and Aisyah Maisarah, for their prayers, love and support. My prayer and gratitude also go to my family for their support, especially my wife Umami Hani and daughter Nur Hanania, I love you all. I wish to express my utmost gratitude and appreciation to all who contributed to this research's success.

ABSTRACT

The granular column technique has been used as a soft ground improvement for over 50 years, whereby stone aggregate and sand are added as the granular material. In order to reduce the use of natural resources, this study introduces a waste product from coal-fired power plants – bottom ash. An in-depth study of bottom ash's morphological and chemical properties is conducted to ensure its suitability as a replacement material and not harmful to the environment. This study adopted the Constant Rate of Strain (CRS) method for loading systems, whereas the majority of other related research uses the incremental loading system by stress control. A series of physical modelling tests are conducted to study the consolidation behaviours and settlements of bottom ash columns, under one dimensional testing. The advantage of CRS is that the consolidation properties can be obtained within only 24 hours, depending on the rate of strain applied. The influence of area improvement ratios and height of columns on the performance of bottom ash columns is investigated through nine physical model tests. Three different area improvement ratios (A_r) of 15%, 20% and 30%, for different length of columns of 50 mm, 100 mm and 150 mm, are used in the experiments. The bottom ash columns are installed in soft ground models prepared from kaolin, which has an undrained shear strength of 10 kPa. In parallel with the experimental investigation, a numerical simulation using Plaxis 3D is performed. An advanced constitutive model is selected for this study namely the Hardening Soil (HS) model, to simulate the models' actual behaviour. The results reveal that the chemical composition and heavy metal traces in bottom ash are minimal and do not exceed regulation standard levels. Hence bottom ash has great potential to be used as a replacement material for stone columns in soft soil improvement works. The area improvement ratio was found to be a very important parameter, which affects the overall performance of the bottom ash columns. Higher area improvement ratios resulted in lower settlements for the composite ground. The value of the compression index, C_c for 30% area improvement ratio obtained is 0.148, compared to 15% for 0.189 at the same height of a column of 150 mm. The results from the numerical simulation corroborated those of the physical modelling, whereby the difference is less than 20%, which is considered acceptable. A consolidation characteristic chart is proposed for predicting settlements based on area improvement ratios and the height of bottom ash columns.

ABSTRAK

Teknik tiang berbutir telah digunakan sepanjang lebih 50 tahun bagi menambah baik tanah lembut dengan menggunakan agregat batu dan pasir sebagai bahan berbutir. Kajian ini memperkenalkan bahan buangan daripada loji kuasa arang batu iaitu abu dasar dalam mengurangkan penggunaan sumber semula jadi. Penyelidikan terperinci mengenai morfologi dan sifat kimia abu dasar telah dijalankan untuk memastikan ia adalah bahan pengganti yang sesuai serta tidak menjejaskan alam sekitar. Kajian ini menggunakan kaedah Kadar Terikan Malar sebagai sistem muatan manakala kebanyakan kajian menggunakan sistem muatan berperingkat melalui kawalan tekanan. Beberapa ujian pemodelan fizikal juga telah dijalankan untuk mengkaji kelakuan dan enapan pengukuhan tiang abu dasar dalam ujian satu dimensi. Antara kelebihan menggunakan CRS adalah sifat pengukuhan dapat diperolehi dalam tempoh 24 jam bergantung kepada kadar terikan yang dikenakan. Pengaruh nisbah pembaikan kawasan dan ketinggian tiang terhadap prestasi tiang abu dasar telah diselidik menggunakan sembilan ujian pemodelan fizikal tiga nisbah pembaikan kawasan yang berbeza (A_r) iaitu 15%, 20%, dan 30% pada tiga ketinggian tiang yang berbeza iaitu 50 mm, 100 mm, dan 150 mm. Tiang abu dasar telah dipasang dalam model tanah lembut yang dibuat daripada kaolin dengan kekuatan ricih tak bersalir 10 kPa. Selari dengan eksperimen ini, simulasi berangka menggunakan Plaxis 3D turut dijalankan. Model juzukan lanjutan iaitu model Pengerasan Tanah / *Hardening Soil* (HS) telah dipilih untuk selaku pelakuan sebenar model-model tersebut. Dapatan kajian menunjukkan komposisi kimia dan sisa logam berat dalam abu dasar adalah minimum dan tidak melebihi standard kawalan. Oleh itu, abu dasar berpotensi untuk digunakan sebagai bahan gantian tiang batu dalam kerja pembaikan tanah lembut. Selain itu, kajian juga mendapati nisbah pembaikan kawasan merupakan parameter yang mempengaruhi prestasi keseluruhan tiang abu dasar. Nisbah pembaikan kawasan yang lebih tinggi menunjukkan enapan yang lebih rendah bagi tanah komposit. Nilai indeks pemampatan, C_c , bagi nisbah pembaikan kawasan 30% adalah 0.148 berbanding 0.189 bagi nisbah 15% pada ketinggian tiang yang sama 150 mm. Keputusan simulasi berangka juga adalah sepadan dengan pemodelan fizikal di mana perbezaannya adalah kurang daripada 20% dan dikira boleh diterima. Carta ciri-ciri pengukuhan telah dicadangkan bagi menjangka enapan berdasarkan hubungan antara nisbah pembaikan kawasan dengan ketinggian tiang abu dasar.

TABLE OF CONTENTS

| | TITLE | PAGE |
|------------------|--|-------------|
| | DECLARATION | iii |
| | DEDICATION | iv |
| | ACKNOWLEDGEMENT | v |
| | ABSTRACT | vi |
| | ABSTRAK | vii |
| | TABLE OF CONTENTS | viii |
| | LIST OF TABLES | xii |
| | LIST OF FIGURES | xiv |
| | LIST OF ABBREVIATIONS | xix |
| | LIST OF SYMBOLS | xx |
| | LIST OF APPENDICES | xxi |
| CHAPTER 1 | INTRODUCTION | 1 |
| 1.1 | Introduction | 1 |
| 1.2 | Problem Statement | 2 |
| 1.3 | Aim and Objectives | 3 |
| 1.4 | Scope and Limitation of Research | 4 |
| 1.5 | Significance of Research | 5 |
| 1.6 | Thesis Outline | 5 |
| CHAPTER 2 | LITERATURE REVIEW | 7 |
| 2.1 | Introduction | 7 |
| 2.2 | Soft Clay | 7 |
| 2.3 | Ground Improvement Technique | 9 |
| 2.3.1 | Stone Column | 11 |
| 2.3.1.1 | Principles of Stone Columns | 12 |
| 2.3.1.2 | Stone Column Design (Diameter, Area Replacement Ratio, | |

| | | |
|------------------|--|-----------|
| | Arrangement and Length/Depth Ratio) | 14 |
| | 2.3.1.3 Unit Cell Concept | 17 |
| | 2.3.1.4 Stress Concentration Ratio, n | 18 |
| | 2.3.1.5 Construction of Stone Columns | 20 |
| | 2.3.1.6 Granular Column Studies | 22 |
| 2.4 | Bottom Ash Utilisation in Industries | 28 |
| | 2.4.1 Physical Properties of Bottom Ash | 34 |
| | 2.4.1.1 Particle Size Distribution | 35 |
| | 2.4.1.2 Specific Gravity | 36 |
| | 2.4.1.3 Permeability | 37 |
| | 2.4.1.4 Compaction | 38 |
| | 2.4.1.5 Strength Characteristics | 39 |
| | 2.4.2 Chemical Properties and Environmental Impact of Bottom Ash | 39 |
| | 2.4.3 Road construction | 43 |
| | 2.4.4 Concreting Works | 44 |
| | 2.4.5 Bottom Ash Physical Modeling Studies | 45 |
| 2.5 | Numerical Modeling | 49 |
| | 2.5.1 Previous studies using PLAXIS 3D | 51 |
| 2.6 | Summary | 59 |
| CHAPTER 3 | RESEARCH METHODOLOGY | 61 |
| | 3.1 Introduction | 61 |
| | 3.2 Materials Collection | 63 |
| | 3.3 Physical and Mechanical Properties Tests | 64 |
| | 3.4 Morphological and Chemical Properties | 67 |
| | 3.5 Physical Modelling Equipment and Tools | 70 |
| | 3.5.1 Testing Chamber | 70 |
| | 3.5.2 Loading Frame | 73 |
| | 3.5.3 Consolidation Fabricated Frame | 75 |
| | 3.5.4 Pneumatic Cylinder | 76 |

| | | |
|------------------|--|------------|
| 3.5.5 | Linear Variable Displacement Transducer (LVDT) | 77 |
| 3.5.6 | Load Cell S-Beam Type | 79 |
| 3.5.7 | Data Acquisition System | 82 |
| 3.5.8 | Pore Water Pressure Transducer | 83 |
| 3.5.9 | Miniature Pressure Transducer | 84 |
| 3.5.10 | Column Installation Equipment | 86 |
| 3.6 | Testing Model Preparation | 89 |
| 3.6.1 | Preparation of Kaolin Slurry for Soft Ground | 89 |
| 3.6.2 | Consolidation Process | 90 |
| 3.6.3 | Vane Shear Test | 92 |
| 3.6.4 | Bottom Ash Columns Installation | 93 |
| 3.6.5 | Miniature Pressure Transducer (MPT) Installation | 97 |
| 3.6.6 | Deformation of Bottom Ash Columns | 97 |
| 3.7 | Testing Programme | 98 |
| 3.8 | Strain Rate Estimation | 99 |
| 3.9 | Procedure of Model Testing | 100 |
| 3.10 | Numerical Modelling | 101 |
| CHAPTER 4 | RESULTS AND DISCUSSION | 107 |
| 4.1 | Introduction | 107 |
| 4.2 | Physical Properties | 107 |
| 4.2.1 | Particle Size Distribution | 109 |
| 4.2.2 | Atterberg Limit | 110 |
| 4.2.3 | Specific Gravity | 111 |
| 4.2.4 | Compaction | 112 |
| 4.2.5 | Permeability | 113 |
| 4.2.6 | Relative Density | 113 |
| 4.2.7 | Direct Shear | 113 |
| 4.2.8 | Oedometer Test | 114 |
| 4.3 | Morphological and Chemical Properties | 115 |
| 4.4 | Physical Modelling | 120 |

| | | |
|-----------------------------|---|------------|
| 4.4.1 | Vane Shear Test | 120 |
| 4.4.2 | Constant Rate of Strain Value | 121 |
| 4.4.3 | Pore Pressure Measurement | 122 |
| 4.4.4 | Effect of Area Improvement Ratio | 123 |
| 4.4.5 | Effect of L/D Ratio | 126 |
| 4.4.6 | Settlement reduction for treated ground using bottom ash columns | 128 |
| 4.4.7 | Stress Concentration Ratio, n | 131 |
| 4.4.8 | Deformation of Bottom Ash Columns | 133 |
| 4.5 | Numerical Modeling Validation | 136 |
| 4.6 | Compression index, C_c and Settlement Prediction | 144 |
| CHAPTER 5 | CONCLUSION AND RECOMMENDATION | 149 |
| 5.1 | Introduction | 149 |
| 5.2 | Conclusions | 149 |
| 5.3 | Research Contributions | 151 |
| 5.4 | Recommendations for Future Research | 152 |
| REFERENCES | | 153 |
| APPENDICES | | 169 |
| LIST OF PUBLICATIONS | | 179 |

LIST OF TABLES

| TABLE NO. | TITLE | PAGE |
|------------------|---|-------------|
| Table 2.1 | Undrained shear strength of soil values | 9 |
| Table 2.2 | Different types of ground improvement techniques | 10 |
| Table 2.3 | <i>L/D</i> ratio on different studies | 15 |
| Table 2.4 | Description of column conditions | 25 |
| Table 2.5 | Bottom ash production globally | 28 |
| Table 2.6 | List of coal-fired power plants in Malaysia as of 2020 | 29 |
| Table 2.7 | Specific gravity test results for bottom ash from Tanjung Bin Power Plant | 37 |
| Table 2.8 | Bottom ash permeability | 37 |
| Table 2.9 | Summary of standard proctor compaction test for bottom ash in Tanjung Bin Power Plant by previous researchers | 38 |
| Table 2.10 | Chemical composition of bottom ash from various sources (%) | 40 |
| Table 2.11 | Maximum concentration of contaminants TCLP in various countries (mg/L) | 41 |
| Table 2.12 | HS model parameters | 51 |
| Table 2.13 | Material properties for HS model | 52 |
| Table 2.14 | Summaries of previous study on granular columns behaviour | 60 |
| Table 3.1 | Laboratory Testing for Kaolin Clay | 64 |
| Table 3.2 | Laboratory Testing for Bottom Ash | 64 |
| Table 3.3 | XRD Matching Element | 67 |
| Table 3.4 | Classification of coal ash | 68 |
| Table 3.5 | Heavy metal traces concern on bottom ash | 69 |
| Table 3.6 | S-Beam Load Cell specifications | 80 |
| Table 3.7 | MPT specifications | 85 |
| Table 3.8 | Consolidation schedule | 92 |
| Table 3.9 | Column to granular material size and ratio | 93 |

| | | |
|------------|---|-----|
| Table 3.10 | Mass of bottom ash required for different heights of columns | 93 |
| Table 3.11 | Total bottom ash estimated for this study | 94 |
| Table 3.12 | List of physical modelling tests | 99 |
| Table 3.13 | Estimating rate of strain values | 100 |
| Table 3.14 | Stage construction modelling phases | 103 |
| Table 4.1 | Properties of bottom ash | 108 |
| Table 4.2 | Engineering properties of kaolin clay | 109 |
| Table 4.3 | Value of C_u and C_c of bottom ash | 110 |
| Table 4.4 | Primary compression index (C_c) for several kinds of soils (Widodo and Ibrahim, 2012) | 114 |
| Table 4.5 | Chemical composition of bottom ash using XRD analysis | 117 |
| Table 4.6 | Heavy metals traces of bottom ash in (mg/L) | 118 |
| Table 4.7 | Mercury traces using FIMS 100 Method | 119 |
| Table 4.8 | Undrained shear strength and height of soft ground model after consolidation | 121 |
| Table 4.9 | Stress concentration ratio, n at peak values at various improvement characteristics | 133 |
| Table 4.10 | Numerical modelling input parameters | 136 |
| Table 4.11 | HSM calibrated parameters | 139 |
| Table 4.12 | Final settlement comparison between numerical and physical modelling | 143 |
| Table 4.13 | C_c values for different A_r at $L/D = 0.25, 0.50$ and 0.75 | 144 |

LIST OF FIGURES

| FIGURE NO. | TITLE | PAGE |
|-------------|---|------|
| Figure 1.1 | Schematic Diagram of Medium Rapid Consolidation Equipment (MRCE) | 2 |
| Figure 2.1 | Quaternary Geological Map of Malaysia for soft soil; a) Peninsular Malaysia; b) Sabah and Sarawak (JMG, 2010) | 8 |
| Figure 2.2 | Possible failure modes of stone columns subjected to vertical loads; a) crushing; b) shear; c) punching and d) bulging (Barksdale and Bachus, 1983) | 12 |
| Figure 2.3 | Different failure mechanisms of a group of stone columns (Kirsch and Kirsch, 2016) | 13 |
| Figure 2.4 | Typical column arrangements, triangular (left) and square grid (right) (McCabe <i>et al.</i> , 2007) | 16 |
| Figure 2.5 | Arrangement of stabilized column (Kitazume and Terashi, 2013) | 16 |
| Figure 2.6 | Unit cell concept (Gniel and Bouazza, 2009) | 18 |
| Figure 2.7 | Stress concentration ratio (n) with respect to: a) Stress on stone columns and b) Time (min) | 19 |
| Figure 2.8 | Vibroflotation technique in stone column construction (Keller, 2014); a) Vibro-compaction and b) Vibro-replacement | 21 |
| Figure 2.9 | Particle size distribution showing the applicability of Vibro-Compaction and Vibro-Replacement techniques (McCabe <i>et al.</i> , 2007) | 22 |
| Figure 2.10 | Test arrangement; a) Load applied on entire surface and b) Load applied on column only (Shivashankar <i>et al.</i> , 2011) | 23 |
| Figure 2.11 | Load settlement behaviour at different thickness; a) Untreated and b) Composite ground | 23 |
| Figure 2.12 | Deformation of a granular column from L to R: silty soil, different thickness of top layer from 1D to 4D and soft clay only (Shivashankar <i>et al.</i> , 2011) | 24 |
| Figure 2.13 | Different conditions of granular columns (I–VI) (Jala <i>et al.</i> , 2021) | 25 |
| Figure 2.14 | Load-settlement chart of different granular column condition (Jala <i>et al.</i> , 2021) | 26 |

| | | |
|-------------|---|----|
| Figure 2.15 | Stiffness of the composite ground at different granular column condition (Jala <i>et al.</i> , 2021) | 27 |
| Figure 2.16 | Single column load test (Das and Pal, 2013) | 27 |
| Figure 2.17 | Fly ash production, 1974 to 2033 in USA (ARTBA, 2015) | 30 |
| Figure 2.18 | Fly ash utilization rate, 1974 to 2033 in USA (ARTBA, 2015) | 31 |
| Figure 2.19 | Bottom ash production, 1974 to 2033 (ARTBA, 2015) | 32 |
| Figure 2.20 | Bottom ash utilization rate 1974 to 2033 (ARTBA, 2015) | 33 |
| Figure 2.21 | Coal ash generation in a Pulverized Coal-Fired Power Plant (Mei-In, 2012) | 34 |
| Figure 2.22 | Grain size distribution obtained from WtE plant in Prague, Czech Republic (Šyc <i>et al.</i> , 2018) | 35 |
| Figure 2.23 | Particle size distribution of kaolin with two bottom ash samples (Marto <i>et al.</i> , 2014) | 36 |
| Figure 2.24 | Single and group bottom ash columns installed in soft clay specimen Muzamir (2013). | 46 |
| Figure 2.25 | The improvement of undrained shear strength at different height penetration ratios (Muzamir, 2013) | 47 |
| Figure 2.26 | Shear strength increment versus height penetration ratio (Yee, 2012) | 47 |
| Figure 2.27 | Vertical stress versus displacement/width of footing (Abuelgasim <i>et al.</i> , 2020b) | 48 |
| Figure 2.28 | Failure pattern of floating columns under vertical loading; a) Granular column and b) Granular column with geotextile encasement | 49 |
| Figure 2.29 | a) Deformation mode; b) Incremental strain and c) Horizontal displacement profile | 53 |
| Figure 2.30 | Simulation of reinforcement system in numerical analysis (Zahmatkesh and Choobbasti, 2010); a) Initial model and b) Deformed mesh | 54 |
| Figure 2.31 | Stress settlement behaviour for different area replacement (%) (Zahmatkesh and Choobbasti, 2010) | 55 |
| Figure 2.32 | Finite element mesh for test model ($s/d = 3$) (Ambily and Gandhi, 2004) | 56 |
| Figure 2.33 | Load vs settlement curves at different s/d ratios (Ambily and Gandhi, 2004) | 56 |

| | | |
|-------------|---|----|
| Figure 2.34 | Vertical load settlement behavior of granular columns (Hasan and Samadhiya, 2017); a) Unreinforced and b) Encased | 57 |
| Figure 2.35 | Deformed shapes of granular column (Hasan and Samadhiya, 2017); a) Laboratory testing and b) FEM | 58 |
| Figure 3.1 | Flowchart of the study | 62 |
| Figure 3.2 | a) Brown Kaolin; b) Bottom ash | 63 |
| Figure 3.3 | Schematic diagram of physical modelling setup | 71 |
| Figure 3.4 | Cylindrical chamber | 72 |
| Figure 3.5 | Baseplate | 72 |
| Figure 3.6 | Top cap | 73 |
| Figure 3.7 | TRI-SCAN Advanced Loading Frame | 74 |
| Figure 3.8 | Beam equipped with holes for pneumatic cylinder and load cell connector | 74 |
| Figure 3.9 | Loading beam setup for; (a) Consolidation stage; (b) CRS Testing stage | 75 |
| Figure 3.10 | Consolidation frame | 76 |
| Figure 3.11 | (a) Pneumatic cylinder; (b) Air compressor unit | 77 |
| Figure 3.12 | (a) LVDT; (b) Digital calliper (Cert no: ST 17183109) | 78 |
| Figure 3.13 | Maximum extension of LVDT slider | 78 |
| Figure 3.14 | LVDT calibration curve | 79 |
| Figure 3.15 | S-Beam Load Cell | 80 |
| Figure 3.16 | Portable data logger and loading frame set up | 81 |
| Figure 3.17 | Load cell calibration curve | 81 |
| Figure 3.18 | Data logger model TDS-540 by TML | 82 |
| Figure 3.19 | Interface of data logger | 82 |
| Figure 3.20 | Pore water pressure transducer from VJ Tech | 83 |
| Figure 3.21 | ADVDPC used for pore water pressure calibration | 84 |
| Figure 3.22 | Pore pressure transducer calibration curve | 84 |
| Figure 3.23 | Three units of MPT | 85 |
| Figure 3.24 | a) MPT calibration; b) MPT screw access | 86 |

| | | |
|-------------|---|-----|
| Figure 3.25 | a) Column casing design; b) Soil extrude design; c) Actual fabricated | 87 |
| Figure 3.26 | Aluminium templates for column installation for different area improvement ratio | 88 |
| Figure 3.27 | (a) Kaolin poured into de-aired water; (b) Homogenous slurry sample | 90 |
| Figure 3.28 | Variation of void ratio in clay with effective vertical stress (Hird and Moseley, 2000) | 91 |
| Figure 3.29 | (a) Vane shear tools; (b) Test points | 92 |
| Figure 3.30 | Templates of column installation; (a) $a_r = 15\%$; (b) $a_r = 20\%$; (c) $a_r = 30\%$ | 94 |
| Figure 3.31 | (a) Soil extruding process; (b) Bottom ash installation | 96 |
| Figure 3.32 | MPT position | 97 |
| Figure 3.33 | Dissect area for samples at $A_r = 30\%$ | 98 |
| Figure 3.34 | CRS testing setup | 101 |
| Figure 3.35 | Modelling the laboratory testing using Plaxis 3D | 103 |
| Figure 3.36 | Treated soft ground using bottom ash column modelled in Plaxis 3D at various L/D and area replacement ratio, A_r (%) | 104 |
| Figure 3.37 | Modified compression and swelling index (Minna and Amardeep, 2017) | 105 |
| Figure 4.1 | Bottom ash collected from Tanjung Bin Power Plant | 108 |
| Figure 4.2 | Particle size distribution of bottom ash and kaolin clay | 109 |
| Figure 4.3 | Plasticity chart for ASTM classification system | 111 |
| Figure 4.4 | Compaction curve for bottom ash | 112 |
| Figure 4.5 | Surface image of bottom ash at different magnification; (a) 5000x; (b) 10000x and (c) 20000x | 115 |
| Figure 4.6 | EDX Spectrograph for bottom ash | 116 |
| Figure 4.7 | XRD pattern for bottom ash | 116 |
| Figure 4.8 | Normalised e -log σ' curve for the untreated sample at a different rate of strain compared with oedometer test | 122 |
| Figure 4.9 | Soil compression characteristic, relating void ratio (e) to an increasing compressive stress (σ') Gregory <i>et al.</i> (2006) | 124 |

| | | |
|-------------|--|-----|
| Figure 4.10 | Normalised e -log σ' curve for different A_r at length/depth ratio of 0.25 | 125 |
| Figure 4.11 | Normalised e -log σ' curve for different A_r at length/depth ratio of 0.50 | 125 |
| Figure 4.12 | Normalised e -log σ' curve for different A_r at length/depth ratio of 0.75 | 126 |
| Figure 4.13 | Normalised e -log σ' curve for different length/depth ratio at $A_r = 15\%$ | 127 |
| Figure 4.14 | Normalised e -log σ' curve for different length/depth ratio at $A_r = 20\%$ | 127 |
| Figure 4.15 | Normalised e -log σ' curve for different length/depth ratio at $A_r = 30\%$ | 128 |
| Figure 4.16 | The settlement reduction percentage S_r of treated ground at different L/D ratio | 129 |
| Figure 4.17 | The settlement reduction ratio β of treated ground at different L/D ratio and A_r | 131 |
| Figure 4.18 | Stress concentration ratio (n) versus applied pressure (kPa) for soft ground treated with bottom ash columns | 132 |
| Figure 4.19 | Bottom ash columns cross-section for H50-C6 | 134 |
| Figure 4.20 | Bottom ash columns cross section for H100-C6 | 135 |
| Figure 4.21 | Bottom ash columns cross section for H150-C6 | 135 |
| Figure 4.22 | Untreated stress settlement curve | 137 |
| Figure 4.23 | Stress strain curve from bottom ash triaxial test | 138 |
| Figure 4.24 | Mohr coulomb plot for bottom ash CU test | 138 |
| Figure 4.25 | Calibration of lab parameters | 139 |
| Figure 4.26 | Stress settlement curve comparison at $L/D = 0.25$ | 140 |
| Figure 4.27 | Stress settlement curve comparison at $L/D = 0.50$ | 141 |
| Figure 4.28 | Stress settlement curve comparison at $L/D = 0.75$ | 142 |
| Figure 4.29 | C_c values for different area improvement ratio, A_r at $L/D = 0.25, 0.50$ and 0.75 | 145 |
| Figure 4.30 | C_c values for different L/D ratio at area improvement ratio, $A_r = 15, 20$ and 30% | 146 |
| Figure 4.31 | Physical modelling setup of floating bottom ash columns in a rectangular model (Rasha <i>et al.</i> , 2019) | 147 |

LIST OF ABBREVIATIONS

| | | |
|---------|---|--|
| CRS | - | Constant Rate of Strain |
| MRCE | - | Medium Rapid Consolidation Equipment |
| JMG | - | Jabatan Metereologi Malaysia |
| IEA | - | International Energy Agency |
| EU | - | European Union |
| OPC | - | Ordinary Portland Cement |
| ARTBA | - | American Road and Transportation Builders Associations |
| ACAA | - | American Coal Ash Association |
| ECOBA | - | European Coal Combustion Products Association |
| USEPA | - | The United States Environmental Protection Agency |
| TCLP | - | Toxicity Characteristic Leaching Procedure |
| FESEM | - | Field Emission Scanning Electron Microscope |
| EDX | - | Energy Dispersive X-Ray Spectroscopy |
| XRD | - | X-Ray Diffraction |
| DOE | - | Department of Environmental |
| ADVDPCC | - | Advanced Pressure/Volume Controller |

LIST OF SYMBOLS

| | | |
|------------|---|---|
| A_r | - | Area improvement ratio |
| H/D | - | Length over depth ratio |
| D/d | - | Diameter of a column to particle size ratio |
| c_u | - | Undrained shear strength |
| A_c/A | - | Unit cell area |
| σ_c | - | Stresses on column |
| σ_s | - | Stresses on soil |
| n | - | Stress concentration number |
| k | - | Coefficient of permeability |
| H_c/H_s | - | Height of columns to height of specimen ratio |
| HSM | - | Hardening soil model |
| SSM | - | Soft soil model |
| D_d | - | Relative density |
| c | - | Cohesion |
| φ | - | Frictional angle |
| C_c | - | Compression index |
| β | - | Settlement reduction ratio |
| S_r | | Settlement reduction percentage |

LIST OF APPENDICES

| APPENDIX | TITLE | PAGE |
|-----------------|-------------------------------|-------------|
| Appendix A | Dry Sieve and Hydrometer Test | 169 |
| Appendix B | Atterberg Limits | 171 |
| Appendix C | Specific Gravity | 172 |
| Appendix D | Relative Density | 173 |
| Appendix E | Constant Head Permeability | 174 |
| Appendix F | MPT Calibration | 175 |
| Appendix G | Certificate of Equipments | 176 |

CHAPTER 1

INTRODUCTION

1.1 Introduction

The Granular column method of soil improvement is an effective, inexpensive, and environmentally friendly approach for the enhancement of soft cohesive soils in term of deformation behaviour. The potential usage of by-products in ground improvement to replace natural materials is a positive step towards environmental sustainability (Arulrajah *et al.*, 2017; Donrak *et al.*, 2016; Phetchuay *et al.*, 2016; Rashid *et al.*, 2017)

Since the 1970s, many granular column researchers have focused on the aspects of end bearing columns, where the ends of the columns reach a firm layer, which is achieved by using the physical modelling test (Ali *et al.*, 2014; Balaam and Booker, 1985; Hughes and Withers, 1974; Malarvizhi and Ilamparuthi, 2004). In contrast, only limited attempts have been made to study the possible usage of the bottom ash as a granular column material to enhance the performance of soft soil. Further tests need to be carried out on these granular columns with different improvement area ratios to understand better the applicability of the technique – particularly in relation to consolidation behaviours.

Therefore, in this study, a series of small-scale physical tests are adopted to investigate settlement behaviours of soft soil reinforced with floating bottom ash columns, with varying area improvement ratios, A_r (%) and lengths, over depth ratios, H/D . A model of soft ground will be prepared inside a rapid consolidation testing rig developed by Raftari (2015) – as shown in Figure 1.1. This is based on the concept of the Consolidation Rate Strain (CRS) method. Using Plaxis 3D, the laboratory testings are simulated and the results were compared. The bottom ash used in this

study underwent physical and chemical characterisation. Toxicity tests were conducted to ensure that the application of bottom ash does not harm the environment and is proven safe to use. The morphological study provides a better understanding of the microstructure of bottom ash and elemental features.

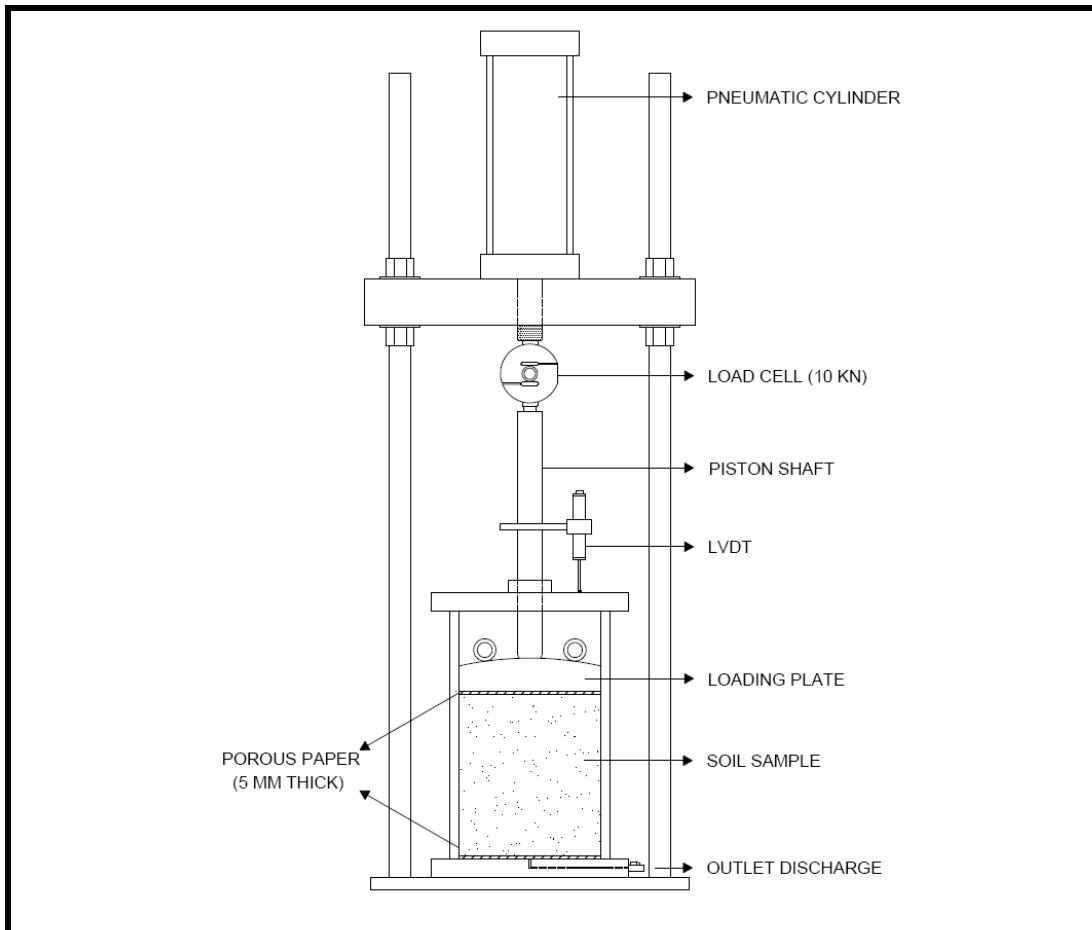


Figure 1.1 Schematic Diagram of Medium Rapid Consolidation Equipment (MRCE)

1.2 Problem Statement

Due to rapid urbanization, soft ground areas are not excluded for use for many construction applications. The nature of soft ground is that it has a high coefficient of compressibility and low undrained shear strength. These result in need for ground improvements to take place. Granular columns are one widely used improvement technique to reduce settlement and increase the rate of consolidation.

However, studies on the usage of bottom ash columns lack from the literature. The use of bottom ash (which is one of the waste materials from coal-fired power plants) helps in reducing the environmental impacts. Plant operators have long complained about the cost of acquiring landfill zones to dispose of bottom ash. It is reported that millions of tons of bottom ash have accumulated up to the present date.

Using a stress control system, most experimental studies of granular columns have been conducted based upon conventional incremental loading consolidation tests. A stress control system takes too long for consolidation testing, where multiple data points and loadings are applied in stages. In contrast, CRS consolidation tests can output a sample's consolidation properties within approximately 24 hours – depending on the rate used, and assume continuous data collection from start to finish. Therefore, this study applies this approach, conducted on bottom ash columns with different area improvement ratios and column lengths, to improve our understanding of their deformation behaviours, using CRS.

1.3 Aim and Objectives

This research aims to determine the characteristic of bottom ash and deformation behaviour of soft soil improved by bottom ash columns using a constant rate of strain consolidation test. The research objectives are:

- (i). To determine the applicability of bottom ash in ground improvement in terms of its engineering characteristic;
- (ii). To investigate the chemical properties and heavy metals traces in bottom ash;
- (iii). To quantify the impact of area improvement and length, over depth ratio, on the settlements of the composite ground, using the physical modelling test;

To develop a relationship between the consolidation properties of a group of bottom ash columns and different area improvement ratios to produce settlement prediction.

1.4 Scope and Limitation of Research

This research investigates the deformation behaviours of soft kaolin, treated with small groups of bottom ash columns by conducting a series of small-scale physical and numerical modelling tests. A total of nine consolidation tests on samples reinforced with a group of bottom ash columns, and one benchmark test without any reinforcement, were conducted using the physical modelling tests. The obtained laboratory results were validated using the numerical modelling simulation.

In order to prepare for the soft ground model and bottom ash columns, two main materials were used. The brown kaolin clay powder (L2B20) (purchased from Kaolin (M) Sdn Bhd) was used to prepare the soft ground model using one-dimensional consolidation analysis. The bottom ash (which was collected from Tanjung Bin Power Plant in Pontian, Johor) was used as the granular material in the columns. This had a particle size range of 63 μ m to 2.36mm.

The dry kaolin clay was reconstituted to slurry form and consolidated in a chamber to form a 200 mm depth, with approximately 10 kPa undrained shear strength, as the ground model. Groups of bottom ash columns of three, four, and six were used. These represent area improvements of 15%, 20% and 30%, respectively, with a 50 mm diameter installed in the soft ground model. As mentioned by Ng and Tan (2014), the selection of area replacement ratio commonly adopted at 20 – 25%. Too high area replacement of more than 40% are insignificant. For each area improvement, three different length/depth ratios were selected at 50mm, 100mm and 150mm, with a ratio of 0.25, 0.50 and 0.75, respectively.

The commercial 3D finite element software – “Plaxis 3D”, was used for the numerical simulation, in order to evaluate and compare results obtained from experimental model tests. Parameters obtained from experimental model tests were used as the inputs to minimize errors.

1.5 Significance of Research

In recent decades academics in industry leaders in the engineering field have developed numerous construction methods to improve soft soils. The stone column technique is one of the most popular approaches and will be used in this study. The application of re-used and recycled materials will benefit the construction industry in terms of resource-efficient. In the construction industry, such as during embankment construction, a large number of materials are required (Marto, et al., 2010). In this situation, coal ash can be utilized, which also helps solve the problem of disposing of coal ash. This study uses bottom ash as a substitute for natural materials, as a ground improvement – in line with sustainable development goals. Investigations into consolidation behaviours based on strain control, is very limited compared to the extensive available studies based on stress control, which many previous researchers have explored.

This research, therefore, focuses on the consolidation behaviour of treated soft ground with bottom ash columns, using a constant rate of strain test instead of a conventional incremental loading method. The outcome will help engineers to understand the relationship between area improvement ratios, and length over depth ratios, for bottom ash columns.

Numerical modelling using Plaxis 3D is used to simulate laboratory physical modelling works. The stress settlement analysis using numerical modelling was predicted and validated for different area improvement ratios and length over depth ratios of bottom ash columns.

1.6 Thesis Outline

This thesis comprises of five chapters. Chapter 1 introduces the research topic and presents a description of the usage of waste products in ground improvement. A problem statement, objectives, scope, limitations, as well as the significance of the research are highlighted in this chapter.

Chapter 2 provides a review of previous literature related to the research topic. The review covers the stone column method as a ground improvement technique and physical and numerical modelling conducted for different cases of granular columns. The physical properties, chemical properties, applications, and physical modelling studies of bottom ash, are also highlighted in this chapter.

Chapter 3 describes the research methodology adopted in this study, outlining the materials, equipment, calibration, laboratory experimentation, and numerical modelling processes. Details of the physical modelling setup, preparation of soft ground samples, and installation of bottom ash columns are also detailed in this chapter.

Chapter 4 presents and discusses the results obtained from the tests described in Chapter 3. These results comprise of bottom ash physical properties, chemical properties, and morphological characteristics. Moreover, this chapter also consists of detailed analyses and results from the physical modelling process and numerical modelling computations.

Conclusions and an overview of the outcomes drawn from this study and recommendations for future research are discussed in Chapter 5.

REFERENCES

- Aboshi, H. I., E., Enoki, M. and Harada, K. (1979). The "Compozer"-a method to improve characteristics of soft clays by inclusion of large diameter sand columns. *Proceedings of the 1979 International conference on soil reinforcement* Paris, 211-216.
- Abubakar, A. U. and Baharudin, K. S. (2012). Properties of concrete using tanjung bin power plant coal bottom ash and fly ash. *International Journal of Sustainable Construction Engineering and Technology*. 3 (2), 56-69.
- Abuelgasim, R., Rashid, A., Bouassida, M., Shien, N. and Abdullah, M. (2020a). Geotechnical Characteristics of Tanjung Bin Coal Bottom Ash. *Proceedings of the 2020a IOP Conference Series: Materials Science and Engineering*, 012055.
- Abuelgasim, R., Rashid, A. S. A., Bouassida, M., Shein, N. K. and Pauh, P. (2020b). Bearing Capacity of Floating Bottom ash Columns: Experimental Study. *International Conference on Geotechnical Engineering (ICGE20)*.
- ACAA. (2017). American Coal Ash Association Retrieved 26.11.2018, from www.aaa-usa.org/Portals/9/Files/PDFs/2017-Charts.pdf
- Afrin, H. (2017). A review on different types soil stabilization techniques. *International Journal of Transportation Engineering and Technology*. 3 (2), 19-24.
- Aggarwal, P., Aggarwal, Y. and Gupta, S. (2007). Effect of bottom ash as replacement of fine aggregates in concrete.
- Ahmad, R. I., Yasufuku, N., Omine, K. and Tsuji, K. (2010). Utilization of Coal Ash As Recycling Material Options in View Point of Geoenvironment *Advances in Environmental Geotechnics* (pp. 715-720): Springer.
- Ahn, J. and Kim, Y.-T. (2012). Consolidation behavior and stress concentration ratio of SCP composite ground. *Marine Georesources & Geotechnology*. 30 (1), 63-85.
- Alhassan, H. M. and Tanko, A. M. (2012a). *Characterization of solid waste incinerator bottom ash and the potential for its use*.

- Alhassan, H. M. and Tanko, A. M. (2012b). Characterization of solid waste incinerator bottom ash and the potential for its use. *International Journal of Engineering Research and Applications*. 2 (4), 516-522.
- Ali, K., Shahu, J. T. and Sharma, K. G. (2014). Model tests on single and groups of stone columns with different geosynthetic reinforcement arrangement. *Geosynthetics International*. 21 (2), 103-118.
- Ambily, A. and Gandhi, S. (2004). Experimental and theoretical evaluation of stone column in soft clay. *ICGGE-2004*. 201-206.
- Amiri, S. T., Dehghanbanadaki, A., Nazir, R. and Motamedi, S. (2020). Unit composite friction coefficient of model pile floated in kaolin clay reinforced by recycled crushed glass under uplift loading. *Transportation Geotechnics*. 22, 100313.
- Arenas, C. G., Marrero, M., Leiva, C., Solís-Guzmán, J. and Arenas, L. F. V. (2011). High fire resistance in blocks containing coal combustion fly ashes and bottom ash. *Waste management*. 31 (8), 1783-1789.
- ARTBA. (2015). *Production and used of coal combustion products in the USA* Washington, D.C.: American road and transportation builders association.
- Arulrajah, A., Abdullah, A., Bo, M. W. and Bouazza, A. (2009). Ground improvement techniques for railway embankments. *Proceedings of the Institution of Civil Engineers-Ground Improvement*. 162 (1), 3-14.
- Arulrajah, A., Yaghoubi, E., Imteaz, M. and Horpibulsuk, S. (2017). Recycled waste foundry sand as a sustainable subgrade fill and pipe-bedding construction material: Engineering and environmental evaluation. *Sustainable Cities and Society*. 28, 343-349.
- Awang, A. R., Marto, A. and Makhtar, A. M. (2011). Geotechnical properties of Tanjung Bin coal ash mixtures for backfill materials in embankment construction. *Ejge*. 16, 1515-1531.
- Awang, A. R., Marto, A. and Makhtar, A. M. (2012). Morphological and strength properties of Tanjung Bin coal ash mixtures for applied in geotechnical engineering work. *International Journal on Advanced Science, Engineering and Information Technology*. 2 (2), 168-175.
- Babu, M. D., Nayak, S. and Shivashankar, R. (2013). A critical review of construction, analysis and behaviour of stone columns. *Geotechnical and Geological Engineering*. 31 (1), 1-22.

- Balaam, N. P. and Booker, J. R. (1985). Effect of stone column yield on settlement of rigid foundations in stabilized clay. *International Journal for Numerical and Analytical Methods in Geomechanics*. 9 (4), 331-351.
- Barksdale, R. D. and Bachus, R. C. (1983). Design and construction of stone columns, vol. I: Turner-Fairbank Highway Research Center.
- Barnes, G. (2016). *Soil Mechanics: Principles and practice* (4th ed.) London, UK: RED GLOBE PRESS.
- Bayat, M., Eslamian, S., Shams, G. and Hajiannia, A. (2019). The 3D analysis and estimation of transient seepage in earth dams through PLAXIS 3D software: neural network. *Environmental Earth Sciences*. 78 (18), 571.
- Bingham, P. and Hand, R. (2006). Vitrification of toxic wastes: a brief review. *Advances in applied ceramics*. 105 (1), 21-31.
- Blasenbauer, D., Huber, F., Lederer, J., Quina, M. J., Blanc-Biscarat, D., Bogush, A., Bontempi, E., Blondeau, J., Chimenos, J. M. and Dahlbo, H. (2020). Legal situation and current practice of waste incineration bottom ash utilisation in Europe. *Waste Management*. 102, 868-883.
- Brinkgreve, R. B. (2005). Selection of soil models and parameters for geotechnical engineering application *Soil constitutive models: Evaluation, selection, and calibration* (pp. 69-98).
- Bruce, W. R. and Tharaniyil, M. P. (2013). *Coal Combustion Products Utilization Handbook* (3rd ed.): We Energies Publication.
- Budhu, M. (2015). *Soil mechanics fundamentals*: John Wiley & Sons.
- Castro, J. and Sagaseta, C. (2011). Deformation and consolidation around encased stone columns. *Geotextiles and Geomembranes*. 29 (3), 268-276.
- CEWEP. (2017). Confederation of European Waste-to-Energy Plants, from www.cewep.eu/wp-content/uploads/2017/09/FINAL-Bottom-Ash-factsheet.pdf
- Chen, J.-F., Li, L.-Y., Xue, J.-F. and Feng, S.-Z. (2015). Failure mechanism of geosynthetic-encased stone columns in soft soils under embankment. *Geotextiles and Geomembranes*. 43 (5), 424-431.
- Chindapasirt, P., Jaturapitakkul, C., Chalee, W. and Rattanasak, U. (2009). Comparative study on the characteristics of fly ash and bottom ash geopolymers. *Waste management*. 29 (2), 539-543.

- Chou, J.-d., Wey, M.-Y., Liang, H.-H. and Chang, S.-H. (2009). Biotoxicity evaluation of fly ash and bottom ash from different municipal solid waste incinerators. *Journal of hazardous materials*. 168 (1), 197-202.
- Cocco, L. and Ruiz, M. (2018). Numerical implementation of hardening soil model. Proceedings of the 2018 *Numerical Methods in Geotechnical Engineering IX, Volume 1: Proceedings of the 9th European Conference on Numerical Methods in Geotechnical Engineering (NUMGE 2018), June 25-27, 2018, Porto, Portugal*, 195.
- Colonna, P., Berloco, N., Ranieri, V. and Shuler, S. (2012). Application of bottom ash for pavement binder course. *Procedia-Social and Behavioral Sciences*. 53, 961-971.
- da Fonseca, A. V. and Dias, H. (2015). Numerical modeling with HSM in Plaxis® of drag anchors of sea floating structures for comparison of Ultimate Holding Capacity (UHC) with limit equilibrium methods. Proceedings of the 2015 *3rd International Symposium on Frontiers in Offshore Geotechnics, ISFOG 2015*,
- Dabo, D., Badreddine, R., De Windt, L. and Drouadaine, I. (2009). Ten-year chemical evolution of leachate and municipal solid waste incineration bottom ash used in a test road site. *Journal of hazardous materials*. 172 (2-3), 904-913.
- Daraei, A., Sherwani, A. F. H., Faraj, R. H., Mohammad, S., Kurdo, S., Zare, S. and Mahmoodzadeh, A. (2019). Stabilization of problematic soil by utilizing cementitious materials. *Innovative Infrastructure Solutions*. 4 (1), 33.
- Das, B. M. (2010). *Principles of geotechnical engineering* USA: Cengage Learning.
- Das, P. and Pal, S. K. (2013). A study of the behavior of stone column in local soft and loose layered soil. *EJGE*. 18, 1777-1786p.
- Donrak, J., Rachan, R., Horpibulsuk, S., Arulrajah, A. and Du, Y. J. (2016). Improvement of marginal lateritic soil using Melamine Debris replacement for sustainable engineering fill materials. [Article]. *Journal of Cleaner Production*. 134, 515-522.
- ECOBA. (2016). European Coal Combustion Products Association Retrieved 24.11.2020, from www.ecoba.org
- EPA. (2020). *Yearbook of Environmental Protection Statistics 2019* Taipei, Taiwan: Environmental Protection Administration.

- Fairbrother, A., Bigham, G., Pietari, J. and Mohsen, F. (2010). Coal ash: hazard, waste, or resources. *Newsl Expon Environ Eco Sci Pract.* 1, 1-11.
- Fattah, M. Y., Shlash, K. T. and Al-Waily, M. J. M. (2011). Stress concentration ratio of model stone columns in soft clays. *Geotechnical Testing Journal.* 34 (1), 50-60.
- Fattah, M. Y., Zabar, B. S. and Hassan, H. A. (2014). An experimental analysis of embankment on stone columns. *Journal of Engineering.* 20 (7), 62-84.
- Fattah, M. Y., Zabar, B. S. and Hassan, H. A. (2015). Soil arching analysis in embankments on soft clays reinforced by stone columns. *Structural Engineering and Mechanics.* 56 (4), 507-534.
- Fergani, S., Mokhtar, K. A. A., Djerbal, L., Pizette, P., Abriak, N.-E. and Nechnech, A. (2020). FEM Simulations of Granular Matter Behaviour Under Triaxial Tests. *Geotechnical and Geological Engineering.* 1-18.
- Garg, V., Sharma, J. K. and Grover, K. D. S. (2019). Stiffening effect on settlement reduction for a single partially stiffened floating granular pile. *Journal of The Institution of Engineers (India): Series A.* 100 (1), 131-138.
- Gavisiddesh, M. and Santosh, G. H. (2013). Experimental Investigation Of Stone Column In Shedi Soil. *International Journal of Engineering Research & Technology.* 2 (10).
- Ghazavi, M. and Afshar, J. N. (2013). Bearing capacity of geosynthetic encased stone columns. *Geotextiles and Geomembranes.* 38, 26-36.
- Gimhan, P., Nasvi, M. and Disanayaka, J. (2018). Geotechnical engineering properties of fly ash and bottom ash: Use as civil engineering construction material.
- Gniel, J. and Bouazza, A. (2009). Improvement of soft soils using geogrid encased stone columns. *Geotextiles and Geomembranes.* 27 (3), 167-175.
- Gofar, N. and Mohamed, R. (2008). Ground improvement by preloading and vertical drain. *Ground improvement & stabilization.* 53.
- Gorman, C. T., Hopkins, T. C., Deen, R. C. and Drnevich, V. P. (1978). Constant-rate-of-strain and controlled-gradient consolidation testing. *Geotechnical Testing Journal.* 1 (1), 3-15.
- Goughnour, R. R. and Bayuk, A. A. (1979). A field study of long term settlements of loads supported by stone columns in soft ground. *Proceedings of the 1979 International conference on soil reinforcement Paris,* 279-285.

- Gregory, A., Whalley, W., Watts, C., Bird, N., Hallett, P. and Whitmore, A. (2006). Calculation of the compression index and precompression stress from soil compression test data. *Soil and Tillage Research*. 89 (1), 45-57.
- Haghi, N. T., Nassiri, S., Shafiee, M. H. and Bayat, A. (2014). Using field data to evaluate bottom ash as pavement insulation layer. *Transportation Research Record*. 2433 (1), 39-47.
- Hamidi, B., Varaksin, S. and Nikraz, H. (2013). Relative density concept is not a reliable criterion. *Proceedings of the Institution of Civil Engineers - Ground Improvement*. 166 (2), 78-85.
- Han, J. (2015a). *Principles and practice of ground improvement*: John Wiley & Sons.
- Han, J. (2015b). Recent research and development of ground column technologies. *Proceedings of the Institution of Civil Engineers-Ground Improvement*. 168 (4), 246-264.
- Han, J. and Ye, S.-L. (2001). Simplified method for consolidation rate of stone column reinforced foundations. *Journal of Geotechnical and Geoenvironmental Engineering*. 127 (7), 597-603.
- Hasan, M., Pangee, N., Nor, M. and Suki, S. (2016a). Shear Strength of Soft Clay Reinforced With Single Encased Bottom Ash Columns.
- Hasan, M., Pangee, N., Nor, M. and Suki, S. (2016b). Shear Strength of soft clay Reinforced with single encased bottom ash columns. *ARP Journal of Engineering and Applied Sciences*. 11 (13).
- Hasan, M. and Samadhiya, N. (2017). Performance of geosynthetic-reinforced granular piles in soft clays: Model tests and numerical analysis. *Computers and Geotechnics*. 87, 178-187.
- Hasan, M. B., Marto, A., Hyodo, M. and Makhtar, A. (2011). The strength of soft clay reinforced with singular and group bottom ash columns. *Electronic Journal of Geotechnical Engineering*. 16.
- Hausmann, M. R. (1990). *Engineering principles of ground modification*.
- Hawkins, A. (2000). General report: The nature of hard rocks/soft soils. Proceedings of the 2000 *The geotechnics of hard soils-soft rocks*, 1391-1402.
- Head, K. H. (1980). *Manual of soil laboratory testing*: Pentech Press London.
- Hemeda, S. (2020). Numerical Analysis of Geotechnical Problems of Historic Masonry Structures. *Geotechnical and Geological Engineering*. 1-9.

- Herman, A. P., Yusup, S., Shahbaz, M. and Patrick, D. O. (2016). Bottom ash characterization and its catalytic potential in biomass gasification. *Procedia engineering*. 148, 432-436.
- Hird, C. and Moseley, V. (2000). Model study of seepage in smear zones around vertical drains in layered soil. *Geotechnique*. 50 (1), 89-97.
- Hjelmar, O., Holm, J. and Crillesen, K. (2007). Utilisation of MSWI bottom ash as sub-base in road construction: first results from a large-scale test site. *Journal of hazardous materials*. 139 (3), 471-480.
- Huat, B. B. K. (2010). *Problematic soil in search for solution* UPM Serdang: Penerbit Universiti Putra Malaysia.
- Hughes, J. M. O. and Withers, N. J. (1974). Reinforcing of soft cohesive soils with stone columns. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*. 11 (11), A234.
- Hussain, M., Tuf, L. D., Yusup, S. and Zabiri, H. (2019). Characterization of coal bottom ash & its potential to be used as catalyst in biomass gasification. *Materials Today: Proceedings*. 16, 1886-1893.
- IEA. (2017). International Energy Agency. *Key world energy statistics* Retrieved 22.11.2018, 2018, from www.iea.org/publications/freepublications/publication/KeyWorld2017.pdf
- Izquierdo, M., López-Soler, Á., Vazquez Ramonich, E., Barra, M. and Querol, X. (2002). Characterisation of bottom ash from municipal solid waste incineration in Catalonia. *Journal of Chemical Technology & Biotechnology*. 77 (5), 576-583.
- Izquierdo, M., Querol, X., Josa, A., Vazquez, E. and López-Soler, A. (2008). Comparison between laboratory and field leachability of MSWI bottom ash as a road material. *Science of the total environment*. 389 (1), 10-19.
- Jala, S. K., Rawat, S. and Gupta, A. K. (2021). Loose Ash Fills Reinforced With the High Confined Encased Stone Columns: Experimental and Numerical Investigation. *Geotechnical and Geological Engineering*. 39 (3), 2503-2520.
- Jamaludin, A. (2009). Energy mix and alternatives energy for sustainable development in Malaysia. *Tokyo, Japan: 9th International Students Summit on Food, Agriculture and Environment in the New Century*.

- Jayaranjan, M. L. D., Van Hullebusch, E. D. and Annachhatre, A. P. (2014). Reuse options for coal fired power plant bottom ash and fly ash. *Reviews in Environmental Science and Bio/Technology*. 13 (4), 467-486.
- Jellali, B., Bouassida, M. and de Buhan, P. (2007). A homogenization approach to estimate the ultimate bearing capacity of a stone column reinforced foundation. *International Journal of geotechnical engineering*. 1 (1), 61-69.
- JMG. (2010). Garispanduan Pemetaan Geologi Kejuruteraan Kawasan Tanah Gambut dan Tanah Lempur. *Kementerian Sumber Asli dan Alam Sekitar*.
- Kassim, K. A., Rashid, A. S. A., Kueh, A. B. H., Yah, C. S. and Siang, L. C. (2016). Criteria of Acceptance for Constant Rate of Strain Consolidation Test for Tropical Cohesive Soil. [Article]. *Geotechnical and Geological Engineering*. 34 (4), 931-947.
- Kayali, O. (2005). High performance bricks from fly ash. *Proceedings of the 2005 Proceedings of the World of Coal Ash Conference, Lexington, Kentucky*,
- Keller. (2014). Ground Improvement Retrieved September 2020, from <https://www.franki.co.za/products/ground-improvement>
- Kim, B. (2003). Properties of coal ash mixtures and their use in highway embankments.
- Kim, B., Prezzi, M. and Salgado, R. (2005). Geotechnical properties of fly and bottom ash mixtures for use in highway embankments. *Journal of Geotechnical and Geoenvironmental Engineering*. 131 (7), 914-924.
- Kim, H.-K. and Lee, H.-K. (2011). Use of power plant bottom ash as fine and coarse aggregates in high-strength concrete. *Construction and Building Materials*. 25 (2), 1115-1122.
- Kim, H. and Lee, H.-K. (2015). Coal bottom ash in field of civil engineering: A review of advanced applications and environmental considerations. *KSCE Journal of Civil Engineering*. 19 (6), 1802-1818.
- Kirsch, K. and Kirsch, F. (2016). *Ground improvement by deep vibratory methods*: CRC press.
- Kitazume, M. and Terashi, M. (2013). *The deep mixing method*: CRC press.
- Kizgut, S., Cuhadaroglu, D. and Samanli, S. (2010). Stirred grinding of coal bottom ash to be evaluated as a cement additive. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*. 32 (16), 1529-1539.

- Kumar, G. and Samanta, M. (2020). Experimental evaluation of stress concentration ratio of soft soil reinforced with stone column. *Innovative Infrastructure Solutions*. 5 (1), 1-11.
- Latifi, N., Horpibulsuk, S., Meehan, C. L., Abd Majid, M. Z., Tahir, M. M. and Mohamad, E. T. (2017). Improvement of problematic soils with biopolymer—an environmentally friendly soil stabilizer. *Journal of Materials in Civil Engineering*. 29 (2), 04016204.
- Lee, K. (1981). Consolidation with constant rate of deformation. *Geotechnique*. 31 (2), 215-229.
- Levandowski, J. and Kalkreuth, W. (2009). Chemical and petrographical characterization of feed coal, fly ash and bottom ash from the Figueira Power Plant, Paraná, Brazil. *International Journal of Coal Geology*. 77 (3-4), 269-281.
- Li, Z., Wang, Q., Xiao, Z., Fan, L., Wang, D., Li, X., Du, J. and Cheng, J. (2020). Behaviors of chromium in coal-fired power plants and associated atmospheric emissions in guizhou, southwest china. *Atmosphere*. 11 (9), 951.
- Liu, X., Ammar, A. S., Lin, H. and Ren, J. (2009). The stress concentration ratio of stone columns under confined condition. Proceedings of the 2009 *International Conference on Transportation Engineering 2009*, 4247-4255.
- Lu, C.-C., Hsu, M. H. and Lin, Y.-P. (2019). Evaluation of heavy metal leachability of incinerating recycled aggregate and solidification/stabilization products for construction reuse using TCLP, multi-final pH and EDTA-mediated TCLP leaching tests. *Journal of hazardous materials*. 368, 336-344.
- Lynn, C. J., Ghataora, G. S. and OBE, R. K. D. (2017). Municipal incinerated bottom ash (MIBA) characteristics and potential for use in road pavements. *International Journal of Pavement Research and Technology*. 10 (2), 185-201.
- Ma, S., Xu, M., Qiqige, X.-H. W. and Zhou, X. (2017). Challenges and Developments in the Utilization of Fly Ash in China. *Int. J. Environ. Sci. Dev*. 8 (11), 781-785.
- Madhav, M. and Miura, N. (1994). Stone columns. Proceedings of the 1994 *International conference on soil mechanics and foundation engineering*, 163-164.

- Malakoff. (2018). Malakoff Corporation Berhad Annual Report 2018 *Powering Excellence*. Kuala Lumpur.
- Malarvizhi and Ilamparuthi. (2007). Comparative study on the behavior of encased stone column and conventional stone column. *Soils and foundations*. 47 (5), 873-885.
- Malarvizhi, S. (2007). Comparative study on the behavior of encased stone column and conventional stone column. *Soils and Foundations*. 47 (5), 873-885.
- Malarvizhi, S. and Ilamparuthi, K. (2004). Load versus settlement of clay bed stabilized with stone and reinforced stone columns. Proceedings of the 2004 *3rd Asian Regional Conference on Geosynthetics*, 322-329.
- Mandal, A. and Sinha, O. (2014). Review on current research status on bottom ash: An Indian prospective. *Journal of The Institution of Engineers (India): Series A*. 95 (4), 277-297.
- Martín-Fernández, J., Olea, R. A. and Ruppert, L. F. (2018). Compositional Data Analysis of Coal Combustion Products with an Application to a Wyoming Power Plant. *Mathematical Geosciences*. 50 (6), 639-657.
- Marto, A., Hasan, M., Hyodo, M. and Makhtar, A. M. (2014). Shear Strength Parameters and Consolidation of Clay Reinforced with Single and Group Bottom Ash Columns. [journal article]. *Arabian Journal for Science and Engineering*. 39 (4), 2641-2654.
- Marto, A., Hassan, M. A., Makhtar, A. M. and Othman, B. A. (2013a). Shear strength improvement of soft clay mixed with Tanjung Bin coal ash. *APCBEE procedia*. 5, 116-122.
- Marto, A., Kassim, K. A., Makhtar, A. M., Wei, L. F. and Lim, Y. S. (2010). Engineering characteristics of Tanjung Bin coal ash. *Electronic Journal of Geotechnical Engineering*. 15, 1117-1129.
- Marto, A., Moradi, R., Helmi, F., Latifi, N. and Oghabi, M. (2013b). Performance analysis of reinforced stone columns using finite element method. *Electronic Journal of Geotechnical Engineering*. 18, 315-323.
- Marto, A., Rosly, N. A., Tan, C. S., Kasim, F., Yunus, N. Z. M. and Moradi, R. (2016). Bearing Capacity Of Soft Clay Installed With Singular And Group Of Encased Bottom Ash Columns. *Jurnal Teknologi*. 78 (7-3).
- McCabe, B. A., McNeill, J. A. and Black, J. A. (2007). Ground improvement using the vibro-stone column technique.

- McKelvey, D., Sivakumar, V., Bell, A. and Graham, J. (2004). Modelling vibrated stone columns in soft clay. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*. 157 (3), 137-149.
- Meguid, M., Saada, O., Nunes, M. and Mattar, J. (2008). Physical modeling of tunnels in soft ground: a review. *Tunnelling and Underground Space Technology*. 23 (2), 185-198.
- Mei-In, M. C. (2012). Fly Ash. *Encyclopedia of Sustainability Science and Technology*. 3820-3843.
- Milani, G., Valente, M. and Alessandri, C. (2018). The narthex of the Church of the Nativity in Bethlehem: a non-linear finite element approach to predict the structural damage. *Computers & Structures*. 207, 3-18.
- Minna, K. and Amardeep, A. (2017). *Soft soil modelling and parameter determination* Sweden.
- Mitchell, J. K. and Soga, K. (2005). *Fundamentals of soil behavior*: John Wiley & Sons New York.
- Mochtar, I. (2006). Empirical Parameters for Soft Soil in Situ. *Civil Engineering Department-ITS*.
- Mohamad, N., Razali, C., Hadi, A., Som, P., Eng, B., Rusli, M. and Mohamad, F. (2016). Challenges in construction over soft soil-case studies in Malaysia. *Proceedings of the 2016 IOP conference series: materials science and engineering*, 012002.
- Mohanty, P. and Samanta, M. (2015). Experimental and numerical studies on response of the stone column in layered soil. *International Journal of Geosynthetics and Ground Engineering*. 1 (3), 1-14.
- Moradi, R. (2016a). *Physical and numerical modelling of bottom ash columns installed in soft clay*. University Teknologi Malaysia
- Moradi, R. (2016b). *Physical and Numerical Modelling of Bottom Ash Columns Installed Soft Clay*. Universiti Teknologi Malaysia, Johor Bahru.
- Moradi, R., Marto, A., Rashid, A. S. A., Moradi, M. M., Ganiyu, A. A., Abdullah, M. H. and Horpibulsuk, S. (2019). Enhancement of soft soil behaviour by using floating bottom ash columns. *KSCE Journal of Civil Engineering*. 23 (6), 2453-2462.
- Muir Wood, D., Hu, W. and Nash, D. F. (2000). Group effects in stone column foundations: model tests. *Geotechnique*. 50 (6), 689-698.

- Murugesan, S. and Rajagopal, K. (2006). Geosynthetic-encased stone columns: numerical evaluation. *Geotextiles and Geomembranes*. 24 (6), 349-358.
- Murugesan, S. and Rajagopal, K. (2010). Studies on the behavior of single and group of geosynthetic encased stone columns. *Journal of Geotechnical and Geoenvironmental Engineering*. 136 (1), 129-139.
- Muzamir, Marto, Hyodo and Makhtar. (2011a). The strength of very soft clay reinforced with singular bottom ash columns. Paper presented at the *International Conference on Advances on Geotechnical Engineering*, Perth, Australia.
- Muzamir, H. (2013). *Strength and compressibility of soft soil reinforced with bottom ash columns*. Universiti Teknologi Malaysia.
- Muzamir Hasan and Aminaton Marto, M. H., Ahmad Mahir Makhtar. (2014). The Strength of Very Soft Clay Reinforced with Singular Bottom Ash Column.
- Muzamir, M., Aminaton, Hyodo, M. and bin Makhtar, A. M. (2011b). The Strength of Soft Clay Reinforced with Singular and Group Bottom Ash Columns. *Electronic Journal of Geotechnical Engineering*, ISSN. 1089-3032.
- Ng, K. and Tan, S. (2014). Design and analyses of floating stone columns. *Soils and Foundations*. 54 (3), 478-487.
- Ng, K. and Tan, S. (2015). Stress transfer mechanism in 2D and 3D unit cell models for stone column improved ground. *International Journal of Geosynthetics and Ground Engineering*. 1 (1), 3.
- Nissa Mat Said, K., Safuan A Rashid, A., Osouli, A., Latifi, N., Zurairahetty Mohd Yunus, N. and Adekunle Ganiyu, A. (2019). Settlement evaluation of soft soil improved by floating soil cement column. *International Journal of Geomechanics*. 19 (1), 04018183.
- Olsson, S., Kärrman, E. and Gustafsson, J. P. (2006). Environmental systems analysis of the use of bottom ash from incineration of municipal waste for road construction. *Resources, conservation and recycling*. 48 (1), 26-40.
- Phetchuay, C., Horpibulsuk, S., Arulrajah, A., Suksiripattanapong, C. and Udomchai, A. (2016). Strength development in soft marine clay stabilized by fly ash and calcium carbide residue based geopolymer. *Applied Clay Science*. 127, 134-142.
- Phillips, J. (1998). *Managing America's solid waste: National Renewable Energy Lab., Golden, CO (US)*.

- Piccinini, D. (2014). Ground improvement with stone columns—Methods of calculating Settlement Improvement Factor: University of Glasgow.
- PLAXIS. (2017). *Material Models Manual*.
- Poulikakos, L., Papadaskalopoulou, C., Hofko, B., Gschösser, F., Falchetto, A. C., Bueno, M., Arraigada, M., Sousa, J., Ruiz, R. and Petit, C. (2017). Harvesting the unexplored potential of European waste materials for road construction. *Resources, Conservation and Recycling*. 116, 32-44.
- Priebe, H. J. (1995). The design of vibro replacement. *Ground engineering*. 28 (10), 31.
- Raftari, M. (2015). *Settlement Behaviour of Soft Soil Stabilized with Soil-cement Columns Using Constant Rate of Strain Method*. Universiti Teknologi Malaysia.
- Ramadoss, P. and Sundararajan, T. (2014). Utilization of lignite-based bottom ash as partial replacement of fine aggregate in masonry mortar. *Arabian Journal for Science and Engineering*. 39 (2), 737-745.
- Ramzi, N. I. R., Shahidan, S., Maarof, M. Z. and Ali, N. (2016). Physical and chemical properties of coal bottom ash (CBA) from Tanjung Bin Power Plant. Proceedings of the 2016 *IOP Conference Series: Materials Science and Engineering*, 012056.
- Rasha, A., Ahmad Safuan, A. R. and Mounir, B. K. N., Mat Said Mohamad Hafeezi, Abdullah. (2019). Settlement of soft soil treated with group of floating bottom ash columns. Paper presented at the *International Conference on Clean Water, Air & Soil (CleanWAS)*, Ho Chi Minh.
- Rashid, A. (2011). *Behaviour of weak soils reinforced with soil columns formed by the deep mixing method*. University of Sheffield.
- Rashid, A. S. A., Latifi, N., Meehan, C. L. and Manahiloh, K. N. (2017). Sustainable improvement of tropical residual soil using an environmentally friendly additive. *Geotechnical and Geological Engineering*. 35 (6), 2613-2623.
- Razak, H. A., Naganathan, S. and Hamid, S. N. A. (2010). Controlled low-strength material using industrial waste incineration bottom ash and refined kaolin. *Arabian Journal for Science and Engineering*. 35 (2B), 53-67.
- Rincón, A., Marangoni, M., Cetin, S. and Bernardo, E. (2016). Recycling of inorganic waste in monolithic and cellular glass-based materials for structural

- and functional applications. *Journal of Chemical Technology & Biotechnology*. 91 (7), 1946-1961.
- Sadon, S. N., Beddu, S., Naganathan, S., Kamal, N. L. M. and Hassan, H. (2017). Coal Bottom Ash as Sustainable Material in Concrete—A Review. *Indian Journal of Science and Technology*. 10 (36).
- Sakleshpur, V., Prezzi, M. and Salgado, R. (2018). Ground Engineering using Prefabricated Vertical Drains: A Review. *GEOTECHNICAL ENGINEERING*. 49 (1), 45-64.
- Sani, M. S. H. M., Muftah, F. and Muda, Z. (2011). The properties of special concrete using washed bottom ash (WBA) as partial sand replacement. *International Journal of Sustainable Construction Engineering and Technology*. 1 (2), 65-76.
- Santos, R. M., Mertens, G., Salman, M., Cizer, Ö. and Van Gerven, T. (2013). Comparative study of ageing, heat treatment and accelerated carbonation for stabilization of municipal solid waste incineration bottom ash in view of reducing regulated heavy metal/metalloid leaching. *Journal of environmental management*. 128, 807-821.
- Sayehvand, S. and Kalantari, B. (2012). Use of grouting method to improve soil stability against liquefaction—a review. *Electronic Journal of Geotechnical Engineering*. 17, 1559-1566.
- Senneca, O., Salatino, P. and Ricci, D. (2013). Development of a dry bottom ash extraction/afterburning system from pulverized fuel co-fired utility boilers. *Proceedings of the Combustion Institute*. 34 (2), 2855-2863.
- Sheeran, D. a. K., R. (1971). Preparation of homogeneous soil samples by slurry consolidation. *J Mater*. 6 (2), 356-373.
- Shivashankar, R., Babu, M. D., Nayak, S. and Rajathkumar, V. (2011). Experimental studies on behaviour of stone columns in layered soils. *Geotechnical and Geological Engineering*. 29 (5), 749.
- Singh, G., Kumar, S., Mohapatra, S. and Kumar, K. (2017). Comprehensive characterization of grounded bottom ash from Indian thermal power plant. *Journal of Residuals Science & Technology*.
- Singh, M. and Siddique, R. (2013). Effect of coal bottom ash as partial replacement of sand on properties of concrete. *Resources, conservation and recycling*. 72, 20-32.

- Singh, M. and Siddique, R. (2014). Strength properties and micro-structural properties of concrete containing coal bottom ash as partial replacement of fine aggregate. *Construction and Building Materials*. 50, 246-256.
- Smith, R. E. and Wahls, H. E. (1969). Consolidation under constant rates of strain. *Journal of the Soil Mechanics and Foundations Division*. 95 (2), 519-539.
- Sondermann, W., Raju, V., Daramalinggam, J. and Yohannes, M. (2016). Practical design of vibro stone columns. Proceedings of the 2016 *The HKIE Geotechnical Division 36th Annual Seminar, Hong Kong*.
- Sormunen, L. A. and Kolisoja, P. (2018). Mechanical properties of recovered municipal solid waste incineration bottom ash: the influence of ageing and changes in moisture content. *Road Materials and Pavement Design*. 19 (2), 252-270.
- Standard, B. (2004). Geotechnical investigation and testing, Identification and classification of soil Part 2. BS EN:14688-2.
- Suki, S. (2015). *A Study of The Undrained Shear Strength of Soft Clay Reinforced with 10 mm and 16 mm Diameter Single Encapsulated Bottom Ash Column*. University Malaysia Pahang.
- Surarak, C., Likitlersuang, S., Wanatowski, D., Balasubramaniam, A., Oh, E. and Guan, H. (2012). Stiffness and strength parameters for hardening soil model of soft and stiff Bangkok clays. *Soils and foundations*. 52 (4), 682-697.
- Sushil, S. and Batra, V. S. (2006). Analysis of fly ash heavy metal content and disposal in three thermal power plants in India. *Fuel*. 85 (17-18), 2676-2679.
- Šyc, M., Krausová, A., Kameníková, P., Šomplák, R., Pavlas, M., Zach, B., Pohořelý, M., Svoboda, K. and Punčochář, M. (2018). Material analysis of Bottom ash from waste-to-energy plants. *Waste Management*. 73, 360-366.
- Taoufiq, L., Laamyem, A., Essediqi, E., Monkade, M. and Zradba, A. (2018). Recycling coal fly ash and coal bottom ash from Moroccan thermal power plant in concrete manufacturing.
- Terzaghi, K., Peck, R. B. and Mesri, G. (1996). *Soil mechanics in engineering practice*: John Wiley & Sons.
- Ti, K. S., Huat, B. B., Noorzaei, J., Jaafar, M. S. and Sew, G. S. (2009). A review of basic soil constitutive models for geotechnical application. *Electronic Journal of Geotechnical Engineering*. 14, 1-18.

- Torkittikul, P., Nochaiya, T., Wongkeo, W. and Chaipanich, A. (2017). Utilization of coal bottom ash to improve thermal insulation of construction material. *Journal of Material Cycles and Waste Management*. 19 (1), 305-317.
- USG. (2005). Recommendations for the design, calculation, construction and quality control of stone columns under building and sensitive structures. France: French Union Syndicale Geotechnique.
- Vaitkus, A., Gražulytė, J., Vorobjovas, V., Šernas, O. and Kleizienė, R. (2018). Potential of mswi bottom ash to be used as aggregate in road building materials. [Article]. *Baltic Journal of Road and Bridge Engineering*. 13 (1), 77-86.
- Vejahati, F., Xu, Z. and Gupta, R. (2010). Trace elements in coal: Associations with coal and minerals and their behavior during coal utilization—A review. *Fuel*. 89 (4), 904-911.
- Widodo, S. and Ibrahim, A. (2012). Estimation of primary compression index (CC) using physical properties of Pontianak soft clay. *International Journal of Engineering Research and Applications (IJERA)*. 2 (5), 2232-2236.
- Wilczyńska-Michalik, W., Dańko, J. and Michalik, M. (2020). Characteristics of particulate matter emitted from a coal-fired power plant. *Polish Journal of Environmental Studies*. 29 (2).
- Wissa, A. E., Christian, J. T., Davis, E. H. and Heiberg, S. (1971). Consolidation at constant rate of strain. *Journal of the Soil Mechanics and Foundations Division*. 97 (10), 1393-1413.
- Yee, Y. M. (2012). *Shear strength of soft soil reinforced with singular and a group of bottom ash columns*. Universiti Teknologi Malaysia.
- Zahmatkesh, A. and Choobbasti, A. (2010). Settlement evaluation of soft clay reinforced by stone columns, considering the effect of soil compaction. *International Journal of Research and Reviews in Applied Sciences*. 3 (2), 159-166.

LIST OF PUBLICATIONS

- 1 Abdullah, M. H., Abuelgasim, R., Rashid, A. S. A., & Mohdyunus, N. Z. (2018). Engineering properties of Tanjung Bin bottom ash. In *MATEC Web of Conferences* (Vol. 250, p. 01006). EDP Sciences.
- 2 Abdullah, M. H., Rashid, A. S. A., Anuar, U. H. M., Marto, A., & Abuelgasim, R. (2019, May). Bottom ash utilization: A review on engineering applications and environmental aspects. In *IOP Conference Series: Materials Science and Engineering* (Vol. 527, No. 1, p. 012006). IOP Publishing.
- 3 Abdullah, M. H., Rashid, A. S. A., Said, K. M., Shien, N. K., and Hasbollah, D. Z. A. (2021). Hardening soil model parameters for sands and clays from laboratory testing. *Journal of Mines, Metals, and Fuels*, 69(8), 159 – 165.
- 4 Moradi, R., Marto, A., Rashid, A. S. A., Moradi, M. M., Ganiyu, A. A., Abdullah, M. H., & Horpibulsuk, S. (2019). Enhancement of soft soil behaviour by using floating bottom ash columns. *KSCE Journal of Civil Engineering*, 23(6), 2453-2462.