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

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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.

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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 Ressurection (Ameen).

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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 diperoleh 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.

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LIST OF ABBREVIATIONS

CRS	-	Constant Rate of Strain
MRCE	-	Medium Rapid Consolidation Equipment
JMG	-	Jabatan Metereologi Malaysia
IEA	-	International Energy Agency
EU	-	Europian Union
OPC	-	Ordinary Portland Cement
ARTBA	-	American Road and Transportation Builders Associations
ACAA	-	American Coal Ash Association
ECOBA	-	Europian 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
ADVDPC	-	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

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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.

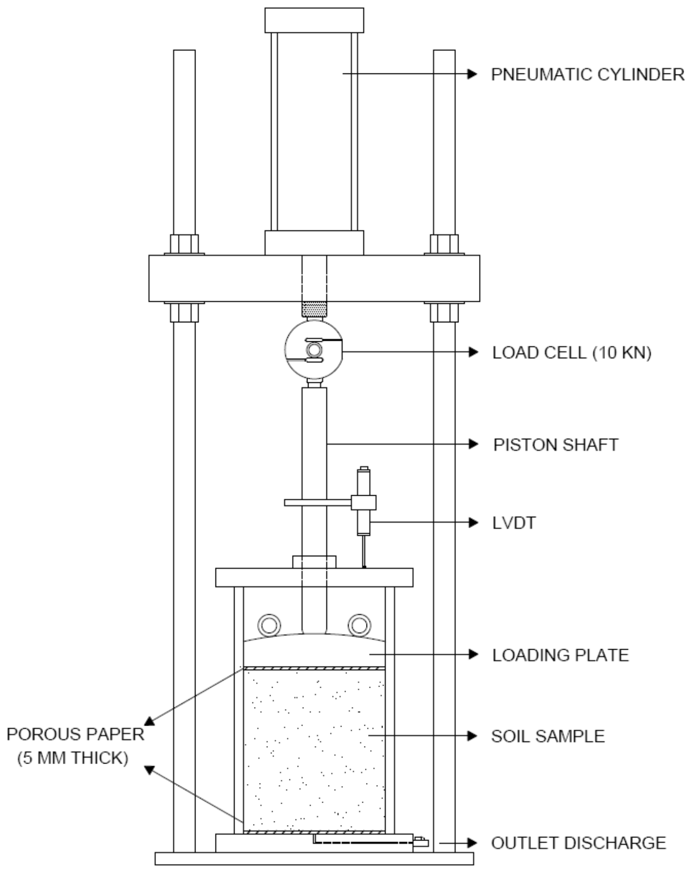

Figure 1.1 Schematic Diagram of Medium Rapid Consolidation Equipment (MRCE)

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 63µm 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.

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