MICROSTRUCTURES OF SOFT CLAY STABILIZED WITH COAL ASH AND CEMENT

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ABSTRACT

As the growth of industries increase electricity demand, the amount of coal ash and waste produced by power plants has significantly increased. Malaysia alone produces approximately 11 million tons of coal annually. For every 2.9 million metric tons of coal that is burned, 1.2 million metric tons of coal ash is produced. Therefore, there is a pressing need to reutilise coal ash waste in a sustainable matter for the good of the environment. The purpose of this study was to identify the macrostructure and microstructure behaviour of marine clay that had been stabilised with coal ash and a minimal amount of ordinary Portland cement (OPC) for use as a subgrade layer in road construction. Very few studies have been conducted on contamination analysis of coal ash as well as mixtures of coal ash and marine clay. In fact, this present study is the first to investigate the performance of marine clay that has been treated with coal ash and OPC with a pre-assessment of load repetition behaviour. The physical properties of all the materials used in this study were examined where necessary. The treated marine clay samples were subjected to an unconfined compressive strength (UCS), California bearing ratio (CBR) as well as a mini tracker tests. Microstructural tests; such as X-ray diffraction (XRD) analysis and energy dispersive X-ray (EDX) spectrometry using a field emission scanning electron microscope (FESEM); as well as toxicity characteristic leaching procedure (TCLP) were also performed. The results of the physical property tests indicated that the use of stabilisers; such as coal ash and OPC; improved the properties of marine clay. The results of the UCS test concluded that the 15% 50BA:50FA sample was the most effective stabiliser as it satisfy the minimum requirements of the Standard Specification for Roadworks for stabilised subgrade layers. During microstructural analysis, XRD analysis showed that the mineral composition intensity of untreated marine clay decreased as the curing duration increased. A new mineral; calcium aluminium silicate hydroxide hydrate (CASH, $Ca_5Si_5Al(OH)O_{17.5}$) was also found to form. The FESEM results showed the surface particles of treated marine clay seemed denser with fewer voids in the structure. In line with the findings of the XRD and FESEM tests, the EDX results confirmed that cementitious product formed was CASH. During the performance testing for subgrade evaluation, the CBR of treated marine clay increased unlike untreated marine clay in both soaked and unsoaked conditions. Of the treated marine clay samples, only the 15% 50BA:50FA sample at Day 7 had a CBR of 12.8%, which was above the minimum 12% required by the Standard Specification for Road Works in Malaysia. The findings of the mini tracker test indicated an increase in the number of cycles when both soaked and unsoaked conditions as well as untreated soil samples were compared. During the contamination analysis, the elemental concentrations of all three samples (fly ash, bottom ash, and treated marine clay) were found to satisfy the regulatory limits outlined by the US Department of Environmental (DOE). However, only the levels of cadmium, selenium, and silver detected in all three samples were within the regulatory limits of the National Standard for Drinking Water Quality. Therefore, marine clay stabilised with coal ash and OPC not only increases in strength but performs better. Moreover, treated marine clay is also safe for the environment.

ABSTRAK

Disebabkan oleh pertumbuhan industri yang memerlukan lebih banyak penjanaan elektrik daripada loji janakuasa, ini telah membawa kepada peningkatan dalam pengeluaran abu arang batu dan jumlah sisa yang tinggi. Kira-kira 11 juta tan arang batu dihasilkan setiap tahun di Malaysia. Bagi setiap 2.9 juta tan metrik arang batu yang dibakar, 1.2 juta tan metrik abu arang dihasilkan. Justeru, terdapat keperluan untuk menggunakan semula sisa abu arang batu sebagai pendekatan yang mampan terhadap alam sekitar. Matlamat kajian ini adalah untuk mengenal pasti struktur makro dan mikrostruktur tanah liat marin apabila distabilkan dengan abu arang batu dengan penambahan jumlah minima simen Portland biasa (OPC) untuk lapisan subgred. Sehingga kini, analisis terhadap pencemaran abu arang batu dan campuran abu arang batu dengan tanah liat marin adalah terhad. Disamping itu, tiada kajian dilakukan terhadap prestasi tanah liat marin yang distabilkan dengan abu arang batu dan simen berkenaan dengan pra-penilaian tingkah laku pengulangan beban.Untuk penyelidikan ini, ujian sifat fizikal telah dilakukan ke atas semua bahan berdasarkan keperluan. Seterusnya, ujian kekuatan mampatan tidak terkurung (UCS), nisbah galas California (CBR) serta ujian 'Mini Tracker' telah dilakukan ke atas sampel tanah liat marin yang dirawat. Tambahan pula, ujian mikrostruktur seperti Field Emission Scanning Electron Microscope (FESEM), X-ray Difraction (XRD), dan Energy Dispersive X-Ray Spectrometer (EDX) dan ujian pencemaran iaitu toxicity characteristic leaching procedure (TCLP) turut dilakukan. Keputusan yang diperolehi daripada ujian sifat fizikal menunjukkan peningkatan dalam sifat tanah. Berdasarkan ujian UCS, jumlah penstabil yang paling berkesan telah dikenal pasti pada 15% 50BA:50FA (mencapai keperluan minimum Spesifikasi Piawaian untuk Kerja Jalan bagi lapisan subgred yang distabilkan). Dari segi analisis mikrostruktur, daripada analisis XRD menunjukkan bahawa komposisi mineral daripada sampel tanah yang tidak dirawat menurun dengan pertambahan masa dan pembentukan mineral baru iaitu kalsium aluminium silikat hidroksida hidrat (CASH, Ca5Si5Al(OH)O17.5). Selain itu, daripada keputusan FESEM, ia menunjukkan bahawa zarah permukaan tanah liat marin yang dirawat kelihatan lebih tumpat dan lompang dalam struktur juga berkurangan. Selain itu, selaras dengan keputusan ujian XRD dan FESEM, keputusan EDX menunjukkan bahawa produk bersimen yang terbentuk adalah CASH. Dari segi ujian prestasi untuk penilaian subgred, CBR tanah liat marin yang dirawat meningkat berbanding dengan tanah liat marin yang tidak dirawat untuk kedua-dua keadaan yang direndam dan tidak direndam. Untuk sampel yang dirawat, hanya sampel 15% 50BA:50FA pada 7 hari dengan nilai CBR sebanyak 12.8%. Ujian mini tracker menunjukkan penambahan bilangan kitaran apabila membandingkan untuk kedua-dua keadaan iaitu yang direndam dan tidak direndam serta tidak dirawat. Untuk analisis pencemaran, ketiga-tiga sampel (FA, BA dan tanah liat marin yang dirawat) melepasi had kawal selia mengikut Jabatan Alam Sekitar Amerika Syarikat (DOE) manakala bagi Piawaian Kebangsaan bagi Kualiti Air Minuman Malaysia untuk ketiga-tiga sampel, hanya unsur kadmium, selenium dan argentum yang melepasi had piawaian. Secara keseluruhan, tanah liat marin yang distabilkan dengan abu arang batu dan simen menunjukkan peningkatan dalam kekuatan serta peningkatan dalam ujian prestasi. Selain itu, tanah liat marin yang dirawat dianggap selamat untuk alam sekitar.

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LIST OF ABBREVIATIONS

AASHTO	-	American Association of State Highway Transportation Officials
ASTM	-	American Society for Testing and Materials
BA		Bottom ash
CI		Clay of intermediate plasticity
CL	-	Clay of low plasticity
EDX	-	Energy dispersive spectroscopy
FESEM	-	Field emission scanning electron microscopy
FA		Fly ash
MC	-	Marine clay
MDD	-	Maximum dry density
OMC	-	Optimum moisture content
UCS	-	Unconfined compressive strength
UCT	-	Unconfined compressive test
USEPA	-	United States of America environment protection agency
USCS		Unified soil classification system
XRD		X-ray diffraction analysis

CHAPTER 1

INTRODUCTION

1.1 Background

The global generation of coal ash waste is increasing at alarming rate. The International Energy Outlook (IEO) 2009 predicted that coal ash waste production in countries, such as India and the United States alone would increase by 88% or 13.33 billion tons between 2006 to 2030 (Tenenbaum, 2009; Alhokabi & Ing, 2019). The total coal ash waste generated worldwide is approximately 600 to 800 million tons (Wang *et al.*, 2005; Hui, Hui and Lee, 2009). In India, 120 coal power plants produce 70% of the country's electricity, which in return produces 115 to 150 million tons of fly ash per year (Lokeshappa & Dikshit, 2011; Jain, 2015; Indiramma, Sudharani, & Needhidasan, 2019). Although fly ash utilisation stood at 58% in 2018, this is still a long way from 100% utilisation (Indiramma, Sudharani, & Needhidasan, 2019). The United States combusts 131 million tons of coal annually, of which only 43% is used (Tenenbaum, 2009). On a yearly basis, China generates approximately 150 million tons of ash (Cao, Selic, & Herbell, 2008) while the United States produces about 125 million tons, Europe about 100 million tons (Kizgut, Cuhadaroglu, & Samanli, 2010), and Thailand produces about four million tons of coal ash waste (Chindaprasirt *et al.*, 2009). To yield 1 megawatt of electricity, 15 to 18.75 tons of coal needs to be burned, which produces 25% to 60% of ash waste and 4.3 to 11 tons of coal waste ash (Asokan, Saxena and Asolekar, 2005; Kizgut, Cuhadaroglu and Samanli, 2010).

Statistically, almost 75 million tons of ash ends up in landfills as waste (Santos, Li, & Amini, 2011). Despite the abundance of fly ash produced, the utilisation rate is still quite low (47%) while only 5.28% of bottom ash is reused (Alhokabi & Ing, 2019). In developed countries, about 80% of fly ash is reutilised in landfills, road construction, agriculture, dam construction, brick manufacturing, ceramics, cellular concrete blocks, and insulating bricks (Indiramma, Sudharani, & Needhidasan, 2019). On a separate note, 2.2 billion tons of cement is produced worldwide annually (Yang, Yang, & Li, 2007). As such, these 2.2 billion tons of fly ash can be reutilised at a 1:1 ratio during concrete mixing (Mehta 1998).

As of 2010, coal power plants generated 40% of Malaysia's electricity (Abubakar, Baharudin, & Technology, 2012). The four coal-fired power stations located in Peninsular Malaysia; the Sultan Salahuddin Abdul Aziz Power Station in Kapar, Selangor, the Tuanku Muhriz Power Station in Lukut, Negeri Sembilan, the Tanjung Bin Power Station in Pontian, Johor, and the Sultan Azlan Shah Power Station in Manjung, Perak; cumulatively generate 1400MW of electricity (Nordin *et al.*, 2016) while three more coal-fired power plants in Sarawak; the PPLS Power Generation Plant, the Sejingkat Power Corporation Plant, and the Mukah Power Station; produce 110W, 100W, and 270W of electricity, respectively (Alhokabi & Ing, 2019). For the purposes of this present study, coal ash was obtained from the Tanjung Bin Power Station in Pontian, Johor, which produces approximately 1620 tons of fly ash and 180 tonnes of bottom ash on a daily basis (Muhardi *et al.*, 2010). The unburned coal produced during coal combustion consists of 80% to 90% of fly ash and 10% to 20% of bottom ash (Abubakar, Baharudin, & Technology, 2012). These statistics indicate an urgent need for fly ash and bottom ash reutilisation as a means of sustainable construction that simultaneously helps reduce the abundance of these by-products.

Fly ash and bottom ash alone cannot stabilise soil due to the absence of pozzolanic minerals (Parsons & Kneebone, 2005; Kurama & Kaya, 2008; Shaheen, Hooda, & Tsadilas, 2014). Therefore, a small amount of chemical-based binder; such as lime and cement; is necessary to provide an element for the pozzolanic reaction and secure the long-term stabilisation process to produce a strong and durable subgrade layer. The use of coal ash and cement to stabilise the subgrade layer during road construction will reduce the need to borrow materials, speed up construction by improving the quality of the subgrade layer, reduce construction cost by reducing pavement thickness as well as the use of expensive natural aggregates. Multiple studies have explored the use of coal ash as a secondary binder alongside traditional additives (Modarres & Nosoudy, 2015; Das & Singh, 2016; J. Ahmad *et al.*, 2016; Eisazadeh, Bhurtel, & Phai, 2019; Indiramma, Sudharani, & Needhidasan, 2019). However, in order to explore a more sustainable approach, this present study used coal ash as the main additive with the help of a secondary binder; more specifically, cement; to stabilise problematic soil.

Bottom ash is commonly reused as a replacement construction material; such as road base material, partial sand replacement in bricks, and fine aggregate in concrete and structural fillers (Syahrul et al., 2010; Alhokabi & Ing, 2019; Azizan et al., 2020). Aggarwal et al. (2007) found out that varying percentages of bottom ash increased the strength of concrete, comparable to that of normal concrete. Higher amounts of bottom ash was also found to reduce the occurrence of concrete deformation due to plastic shrinkage (Andrade, Rocha, & Malik, 2007). Azizan et al. (2020) replaced the use of fine aggregates in concrete with bottom ash and found that bottom ash could substitute sand as it absorbs more water, which increases its strength, without jeopardising cost. However, there is little to no research on the use of bottom ash to stabilise soil as bottom ash is still considered a scheduled waste. As such, this limits the practical application of bottom ash as a soil stabiliser as there are certain guidelines to adhere to; such as those of the Department of Environment (DOE); as its effect on the environmental remains to be explored. According to the American Coal Ash Association (2008), only 2.3% of bottom ash is reutilised as a soil stabiliser in the United States. Therefore, there is a need to examine its effects on soil.

The primary purpose of this present study was to investigate the suitability of a subgrade layer that had been stabilised with an optimum combination of coal ash and a minimum amount of ordinary Portland cement (OPC). Pavement performance, which included both soaked and unsoaked California bearing ratio (CBR) tests, as well as a Mini Tracker test was conducted. A microstructural test was performed to verify the effects of the strength increase while a contamination analysis was conducted to determine if fly ash, bottom ash, as well as a mixture of fly ash-bottom ash-soil was environmentally safe.

1.2 Problem Statement

Marine clay is usually found in coastal regions as well as offshore and ocean beds (Rajasekaran & Narasimha Rao, 1997). It is considered a problematic soil due to its low strength and high compressibility. Marine clay is also highly susceptible to swelling and shrinkage according to changes in moisture content (Rao *et al.*, 2012). As such, this type of soil is considered unsuitable for any construction or development upon it. For the purposes of this study, marine clay was obtained from a housing site in Iskandar Puteri, Johor Bahru. Due to the expansion of existing infrastructure as well as new development projects in this already crowded and mature area, there is the dilemma of land scarcity. Therefore, there is a need to stabilise the marine clay in this region before structures can be safely constructed upon it.

As previously mentioned, coal ash is abundantly available. Moreover, due to the high costs involved in constructing ash ponds to dump this waste, power plants are exploring the feasibility of using existing coal ash deposits in a beneficial and innovative way in order to make room to dispose of newly generated coal ash when it arises. There are two methods of disposing of coal ash; wet or dry (López-Antón *et al.*, 2007). In the dry method, coal ash is dumped into landfills and mixed with waste gypsum (Sathonsaowaphak, Chindaprasirt, & Pimraksa, 2009) while in the wet method, both fly ash and bottom ash are mixed with water to form a slurry (Chakraborty & Mukherjee, 2009) that is then dumped into lagoons or ponds (Asokan, Saxena, & Asolekar, 2005; Kim & Prezzi, 2008). The wet method of coal ash disposal is more environmentally detrimental than the dry method (Hansen, Notten, & Petrie, 2002). Furthermore, although Malaysia accumulates approximately 76% of all its solid waste, only 5% of it is recycled while the remaining 95% ends up in landfills (Papargyropoulou *et al.*, 2011). This indicates the alarming need to reuse coal ash, to stabilise marine clay in this case. It is hoped that by reusing coal ash in this manner, it would negate the environmental pollution caused by the abundance of waste in landfills as well as reduce the cost of creating ponds to dispose of coal ash. Reusing coal ash also supports sustainability, which is one of the initiatives that the Malaysian government is trying to implement.

The Environmental Quality Act, 1974 classified both fly ash and bottom ash as an SW 104 Scheduled Waste. Therefore, the use of fly ash and bottom ash requires prior authorisation from the Malaysian Department of Environment (DOE). While coal ash has been utilised for many things, the use of fly ash and bottom ash is less widely accepted. This is primarily due to a lack of guidelines for its use , & Technology, 2012). However, the number of studies exploring the use of bottom ash has increased over the years. Therefore, in order for both fly ash and bottom ash to be reused on a much larger scale, its long-term environmental safety needs to be proven. Although some researchers deem coal ash to be non-hazardous, hazardous effects could develop over prolonged and extensive dumping (Twardowska and Szczepanska, 2002).

This study explored the feasibility of stabilising marine clay with coal ash as the primary additive and OPC as the secondary additive. OPC is extensively used as a binder in the construction industry due to its pozzolanic properties. Multiple extant studies have shown that the addition of OPC and coal ash increases the strength and workability of soil, especially clay soil (Nontananandh & Boonyong, 1998; J. Ahmad *et al.*, 2016; Yoobanpot, Jamsawang, & Horpibulsuk, 2017; Jamaludin *et al.*, 2020). Furthermore, OPC is a binder that lessens the leachability of heavy metals as cement immobilises heavy metals (Giergiczny & Krol, 2008; Chen *et al.*, 2009; Copper *et al.*, 2011).

1.3 Research Aims and Objectives

The purpose of this present study was to evaluate the macrostructure and microstructure behaviour of marine clay as a subgrade layer when stabilised with coal ash and a small quantity of OPC. Coal ash was the main additive while OPC was the secondary additive. The objectives of this study were:

1. To characterise the materials used in this study; namely coal ash and marine clay.

2. To analyse the effect that compositions containing varying quantities of coal ash and OPC had on strength using microstructural verification

3. To investigate the performance of subgrade layers made of treated and untreated marine clay.

4. To determine the environmental effects of fly ash and bottom ash on soil.

1.4 Scope of the Study

This laboratory-based study experimented using coal ash as the main soil stabiliser and OPC as the secondary soil stabiliser in marine clay. Marine clay was obtained from a site in Iskandar Puteri, Johor while coal ash was obtained from the Tanjung Bin Power Plant in Johor and OPC was obtained from the Structural Lab (D04) at Universiti Teknologi Malaysia (UTM). All experiments were carried out at the Geotechnical lab (D03). This study used coal ash, which consists of fly ash and bottom ash, as the main stabiliser while OPC was used as the secondary stabiliser.

All tests were conducted in accordance with the British Standard (BS) 1377:1990. In order to determine physical properties; such as the Atterberg limits; of the samples, particle size distribution, specific gravity, compaction, pH, and moisture content were examined. Microstructural tests were also conducted on the samples using field emission scanning electron microscopy (FESEM), X-ray diffraction (XRD), and energy dispersive X-ray spectrometer (EDX) when needed. To determine the optimum mixture, samples that had been stabilised with both the main and secondary stabilisers were subjected to the unconfined compression test to evaluate the unconfirmed compressive strength (UCS) of the samples. The selected sample then underwent soaked and unsoaked CBR, a Mini Tracker test, and toxicity characteristic leaching procedure (TCLP).

1.5 Significance of the Study

At present, not many studies have used a mini tracker test to assess the performance of subgrades made with marine clay or marine clay stabilised with coal ash and cement. Over the years, mini tracker tests have been conducted on pavement materials; such as recycled concrete and tyre aggregate mixtures, rock asphalt mixtures, and stone mastic asphalt; as well as cement-treated materials; such as limestone and silty sand soil (Blerk & Scullion, 1995; Hafeez, Kamal, & Mirza, 2014; Howard, Sullivan, & Anderson, 2016; Arulrajah *et al.*, 2020; Ren *et al.*, 2020).

There is also limited contamination analysis data available on the use of coal ash alone as well as coal ash and marine clay mixtures. Only Modarres and Nosoudy (2015) investigated the environmental effects of using coal ash and lime with clay. As such, very little research has been done on contamination analysis for both fly ash and bottom ash, particularly marine clay and cement. Therefore, the findings of this present study add knowledge and insight to this scarce body of work.

This study determined if coal ash and minimum quantities of OPC could effectively stabilise marine clay and improve its properties for use as a subgrade layer in road construction. As stabilising this problematic soil would make it safe and useful for construction purposes, it would help reduce the amount of coal ash that ends up at the ash ponds of power plants. Furthermore, multiple extant studies have failed to investigate fly ash to bottom ash ratio. This data is important to determine whether varying ratios of both would significantly affect the end product.

1.6 Thesis Organisation

This thesis comprises of five chapters. Chapter 1 contains the background, problem statement, research aims and objectives, scope of the study, and significance of the study. Chapter 2 reviews relevant extant literature; such as the background of the marine clay and soil additives used in this study; namely coal ash and cement. The macrostructural and microstructural characteristics of treated soil as well as the contamination study of soil and materials were also discussed. The methodology of this research is elaborated in Chapter 3. This includes the testing procedures, sample preparations, and the standards that were used and referred to throughout this study. Chapter 4 provides an analysis and discusses the results of this research. The characterisation of the untreated materials as well as the results of the macrostructural study, microstructural study, and performance testing of treated soil as well as contamination assessment are provided. Lastly, Chapter 5 summarises this thesis and suggests recommendations for future studies.

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