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Characterisation of Expansive Soils Treated with Hydrated Lime, Bottom Ash and Bagasse Ash

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under the supervision of A/Prof Hadi Khabbaz and A/Prof Behzad Fatahi

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Minh Thang Le declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Civil and Environmental Engineering at the University of Technology Sydney. This thesis is wholly my own work unless otherwise referenced or acknowledge. In addition, I certify that all information sources and literature used are indicated in the thesis. This document has not been submitted for qualifications at any other academic institution. This research is supported by the Australian Government Research Training Program.

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Date: 30/06/2021

DEDICATION

I would like to dedicate this Doctoral dissertation:

To my respective mother, Nguyen Thi Ha Mat and my passed-away father, Le Mau Thao

For their endless love, supports, inspiration and sacrifices.

To my supportive wife, Le Diem Thu

For her patient love, sacrifices, supports and understanding

To my lovely sister, Le Thi Nhu Quynh

For her encouragement and supports

ABSTRACT

Expansive soil is regarded as a kind of problematic soil that has a low bearing capacity and excessive volume change (shrinkage or swelling) under climate change or changes of ambient moisture. These characteristics are seen as pivotal factors that pose a threat to the foundations of civil structures, such as pavements, highways, light buildings, and canal linings and beds. Hence, it has a necessity of reducing the shrinkage-swelling potential of expansive soil and enhancing its strength so that the improvement can minimise adverse impacts of soil. To stabilise expansive soil, lime treatment is a common technique to limit its shrinkage-swelling potentials because the treatment significantly alters the hydromechanical and physical features of the soil. When the treatment includes ash materials, the modification from both lime and the silicate materials in soil properties becomes stronger than each binder does.

In this study, readily available waste by-products rich in silica, including bottom ash and bagasse ash collected in Australia, were utilised to mix with hydrated lime for stabilising expansive soils. The study includes extensive programs of experiments in electrical, physical, mechanical and micro-structural properties of stabilised soils, followed by a numerical analysis on an embankment on soft soils in Australia. Particularly, electrical conductivity methods were carried out to determine the optimum ratio of ash to lime in their treatments, based on pozzolanic reactivity of ash mixtures. The methods are novel because there is a lack of studies on predicting behaviours of two-ash-lime treated soils by using electrical conductivity tests. For this purpose, modified electrical conductivity (EC) methods were proposed to estimate the changes in loss of conductivity when bottom ash and bagasse ash were added to lime-soil suspensions. Due to the testing credibility, a homogeneous expansive soil was artificially constituted from kaolinite (65%), bentonite (30%) and sand (5%). When mixing ash with soil and lime, three EC tests were suggested, namely Tests A, B and C. While Test A was used for bagasse ash in various maximum particle sizes (i.e., 75, 150 and 425 μm), Test B was designed for bottom ash excluded from the gravel size particles. When it comes to combining bottom ash and bagasse ash for soil stabilisation, Test C was employed, in which the optimal ratio of bottom ash to bagasse ash was determined in their aqueous solutions. As testing results, the findings showed that with 5% hydrated lime, the optimal content for each ash was 25% for bottom ash and 15% for bagasse ash. However, when two ashes were combined, the ratio was 17.5% for bottom ash and 7.5% for bagasse ash. The combination ratios are based on the total dry mass of dry soil and ash, resulting in 75% for soil content.

As for the characterisation of soils treated with lime, bottom ash, and bagasse ash, soil samples with 5% lime and 25% bottom ash were superior to other treated soils in most mechanical results. Bottom-ash-lime-treated soil had the lowest swelling ratio of 2.6%, the highest pre-consolidation pressure of 463 kPa, unconfined compressive strength (*UCS*) of 2.1 MPa, unsoaked California bearing ratio (*CBR*) of 84%, soaked *CBR* of 128% after 62 days of saturation, and the stable and largest small-strain shear modulus (G_{max}) of 653 MPa after one year curing for saturated samples. Meanwhile, the soil specimens with 5% lime, 17.5% bottom ash and 7.5% bagasse ash had the lowest linear shrinkage of 12.2 %, the highest 90-day matric suction of 298 kPa, and the largest G_{max} of 675 MPa in saturated specimens after 28 days of curing. These improvements have been explained via scanning electron microscope (SEM) analysis. The analysis indicated a formation of reticular networks, where calcium silicate hydrate (CSH), ettringite and lime coexist in the interfacial transition zone between bagasse ash and bottom ash. Meanwhile, the soils stabilised with 5% lime and 15% bagasse ash still have their advantages in triaxial properties with high values of friction angle and cohesion. As a result, these beneficial properties assisted in reducing the lateral movement of a working platform on the topsoil layer under a modelled embankment in Ballina, NSW, Australia. The numerical outcomes from the PLAXIS program suggested that using both bagasse ash for lime treatment on the soil surface and bottom ash for lime-treated soil columns is the optimal solution to effectively decrease the settlement and horizontal deformation of the ground under the embankment. This study also provides a detailed discussion on the relationships of electrical conductivity results with swell-shrinkage and strength behaviours of ash-lime-treated soils and the evolution of G_{max}. In summary, this investigation can facilitate comprehending the complex behaviour of expansive soils treated with hydrated lime, bottom ash and bagasse ash, incorporating the electrical conductivity measurements and predicting their behaviour in the field through modelling analysis.

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LIST OF PUBLICATIONS

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NOTATIONS

Latin notations

C Concentration

C_c Compression index

C_s Swelling index

C_α Creep index

c_k Change in permeability

e Void ratio

e_0 Initial void ratio

E Young's modulus

EC Electrical conductivity

I_p Plastic index

G_{max} Small-strain shear modulus

G_s Specific gravity

K_0 At-rest earth pressure coefficient

k_x Vertical permeability

k_y Horizontal permeability

LC_0 Initial loss in conductivity

n Porosity

pH Potential of hydrogen

PI Plastic index

PL Plastic limit

RC Rate of electrical conductivity

S_r Degree of saturation

t Time

T Temperature

T_c Temperature compensation coefficient

V_s Shear wave velocity

LL Liquid limit

Greek notations

γ Unit weight

κ Kappa

λ Lambda

ν Poisson's ratio

σ'_v Effective stress

Φ' Friction angle

Acronyms

CBR California bearing ratio

CRS Constant rate of strain

CSH Calcium silicate hydrate

CASH Calcium aluminum silicate hydrate

BA Bagasse ash

BO Bottom ash

BB Bottom ash – bagasse ash

EDX Energy dispersive x-ray spectroscopy

ITS Indirect tensile strength

IL Incremental loading

KBS Kaolinite – bentonite – sand

L Lime

LVDT Linear variable differential transformer

MC	Mohr Coulomb
MCC	Modified cam clay
MDD	Maximum dry density
MSH	Magnesium silicate hydrate
OCR	Over consolidation ratio
OMC	Optimum moisture content
PVDs	Prefabricated vertical drains
UCS	Unconfined compressive strength
SEM	Scanning Electron Microscopy
SSC	Soft soil creep
XRD	X-ray diffraction