# ENGINEERING AND ENVIRONMENTAL ASSESSMENT OF CRUSHED SLAG AND FLY ASH IMPROVED MARGINAL LATERITIC SOIL FOR PAVEMENT APPLICATIONS

**Phuttipong Sudla**



**A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Construction and Infrastructure Management**

**Suranaree University of Technology**

**Academic Year 2018**

# การประเมินด้านวิศวกรรมและผลกระทบด้านสิ่งแวดล้อมของตะกรันเหล็กโม่และเถ้าลอยปรับปรุงดินลูกรังด้อยคุณภาพในงานทาง

**นายพุฒิพงศ์ สุดหล้า**



**วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต**

**สาขาวิชาการบริหารงานก่อสร้างและสาธารณูปโภค**

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**ปีการศึกษา 2561**

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Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

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พุฒิพงศ์ สุดหล้า : การประเมินด้านวิศวกรรมและผลกระทบด้านสิ่งแวดล้อมของตะกรันเหล็กโม่และเถ้าลอยปรับปรุงดินลูกรังด้อยคุณภาพในงานทาง (ENGINEERING AND ENVIRONMENTAL ASSESSMENT OF CRUSHED SLAG AND FLY ASH IMPROVED MARGINAL LATERITIC SOIL FOR PAVEMENT APPLICATIONS) อาจารย์ที่ปรึกษา : ศาสตราจารย์ ดร.สุขสันติ์ หอพิบูลสุข, 116 หน้า.

วิทยานิพนธ์นี้มีวัตถุประสงค์เพื่อศึกษาความเป็นไปได้ในการใช้ตะกรันเหล็กโม่และเถ้าลอย เพื่อปรับปรุงดินลูกรังด้อยคุณภาพ ให้สามารถนำมาใช้เป็นวัสดุงานโครงสร้างทางอย่างยั่งยืน โดยวิทยานิพนธ์ประกอบด้วย 3 ส่วนได้แก่ ส่วนแรกศึกษาแนวทางในการใช้ลูกรังด้อยคุณภาพที่ปรับปรุงด้วยตะกรันเหล็กโม่เป็นวัสดุทางเลือกที่ใช้ในการก่อสร้างโครงสร้างทางชั้นวัสดุคัดเลือก โดยการเตรียมอัตราส่วนผสมของตัวอย่างที่ผสมดินลูกรังด้อยคุณภาพต่อตะกรันเหล็กโม่ในอัตราส่วนโดยน้ำหนัก (50/50, 60/40, 70/30, 80/20 และ 90/10) และทำการทดสอบในห้องปฏิบัติการทางวิศวกรรมปฐพี การทดสอบประกอบด้วยการหาขนาดคละของวัสดุมวลรวม, ค่าความถ่วงจำเพาะ, ค่าการดูดซึมน้ำ, ค่าความต้านทานการสึกหรอ, การบดอัดแบบสูงกว่ามาตรฐาน และแคลิฟอร์เนียร์แบริ่งเรโช (CBR) ผลการทดสอบพบว่าตะกรันเหล็กโม่เป็นวัสดุที่ไม่มีคุณสมบัติความเหนียว (non-plastic) และมีค่าต้านทานการสึกหรอต่ำหรือมีความคงทนสูง ดังนั้น ดินลูกรังด้อยคุณภาพที่มีตะกรันเหล็กโม่ผสม จึงสามารถพัฒนาคุณสมบัติด้านการลดคุณสมบัติความเหนียว เพิ่มความคงทนต่อการสึกหรอสูงขึ้น, เพิ่มค่าแคลิฟอร์เนียร์แบริ่งเรโช และลดคุณสมบัติการบวมตัว ผลการทดสอบยังแสดงให้เห็นว่าคุณสมบัติทางกายภาพและคุณสมบัติทางกล ของดินลูกรังด้อยคุณภาพที่ถูกแทนที่ด้วยตะกรันเหล็กโม่ปริมาณร้อยละ 10 สามารถนำมาใช้เป็นวัสดุคัดเลือกตามมาตรฐานกรมทางหลวง

ส่วนที่สองศึกษาคุณสมบัติด้านความหนาแน่น กำลังอัดและความคงทนต่อสภาวะเปียกสลับแห้ง ของตัวอย่างดินลูกรังที่ผสมตะกรันเหล็กโม่และเถ้าลอยโดยน้ำหนัก (70:30:0, 70:15:15 และ 70:0:30) และปริมาณปูนซีเมนต์ที่อัตราส่วนต่าง ๆ ผลการศึกษาพบว่าคุณสมบัติด้านกำลังอัดเพิ่มขึ้นตามปริมาณตะกรันเหล็กโม่และเถ้าลอยที่แทนที่เข้าไปอย่างมีนัยสำคัญ เช่นเดียวกับกำลังอัดที่เพิ่มขึ้น และแคลิฟอร์เนียร์แบริ่งเรโชแบบแช่น้ำและความคงทนต่อสภาวะเปียกสลับแห้ง มีค่าเพิ่มขึ้นตามปริมาณตะกรันเหล็กโม่และเถ้าลอย ดินลูกรังที่แทนที่ด้วยตะกรันเหล็ก โม่และเถ้าลอยร้อยละ 70:30:0 และปริมาณปูนซีเมนต์ร้อยละ 3 อยู่ในเกณฑ์ใช้เป็นวัสดุรองพื้นทางซีเมนต์ ในขณะที่ ดินลูกรังที่แทนที่ด้วยตะกรันเหล็กโม่และเถ้าลอยร้อยละ 70:15:15 และ 70:0:30 ผสมปูนซีเมนต์ร้อยละ 3 อยู่ในเกณฑ์ใช้เป็นวัสดุชั้นพื้นทางตามมาตรฐานกรมทางหลวง ตัวอย่างดินลูกรังที่ผสมตะกรันเหล็กโม่ร้อยละ 30 ผสมด้วยปูนซีเมนต์ร้อยละ 3 มีความคงทนต่อสภาวะเปียกสลับแห้ง

มากกว่า 7 วงรอบ ดินลูกรังที่ผสมตะกรันเหล็กโม่และเถ้าลอยร้อยละ 70:15:15 และ 70:0:30 ผสมปูนซีเมนต์ร้อยละ 3 มีความคงทนต่อสภาวะเปียกสลับแห้งมากกว่า 12 รอบ และดินลูกรังที่ผสมตะกรันเหล็กโม่และเถ้าลอยร้อยละ 70:30:0, 70:15:15 และ 70:0:30 ผสมปูนซีเมนต์ร้อยละ 5 มีความคงทนต่อสภาวะเปียกสลับแห้งมากกว่า 12 รอบ

ส่วนท้ายของวิทยานิพนธ์ประเมินผลกระทบด้านสิ่งแวดล้อม โดยศึกษาความสามารถในการชะละลายโลหะหนักของตัวอย่างดินลูกรังที่ผสมตะกรันเหล็กโม่และเถ้าลอยพร้อมด้วยปูนซีเมนต์ เมื่อเปรียบเทียบกับมาตรฐานสากล ผลการศึกษาการชะละลายโลหะหนักพบว่าดินลูกรังที่แทนที่ด้วยตะกรันเหล็กโม่และเถ้าลอยร้อยละ 70:15:15 และปริมาณปูนซีเมนต์ร้อยละ 5 สามารถใช้ในงานโครงสร้างทางได้อย่างปลอดภัยเนื่องจากความเข้มข้นของโลหะหนักที่ชะละลายอยู่ในช่วงที่ยอมรับได้ ผลของการศึกษาครั้งนี้จะเป็นการส่งเสริมให้มีใช้ตะกรันเหล็กโม่ และเถ้าลอยซึ่งเป็นวัสดุเหลือใช้ในงานก่อสร้างโครงสร้างทางที่เป็นมิตรต่อสิ่งแวดล้อมต่อไป



สาขาวิชา การบริหารงานก่อสร้างและสาธารณูปโภค ลายมือชื่อนักศึกษา____________

ปีการศึกษา 2561 ลายมือชื่ออาจารย์ที่ปรึกษา____________

PHUTTIPONG SUDLA : ENGINEERING AND ENVIRONMENTAL ASSESSMENT OF CRUSHED SLAG AND FLY ASH IMPROVED MARGINAL LATERITIC SOIL FOR PAVEMENT APPLICATIONS. THESIS ADVISOR : PROF. SUKSUN HORPIBULSUK, Ph.D., 116 PP.

MARGINAL LATERITIC SOIL/CRUSHED SLAG/FLY ASH/CEMENT /LEACHATE

This thesis aims to study the possibility of using crushed slag (CS) and fly ash (FA) to stabilize marginal lateritic soil (LS) to be a sustainable stabilized pavement material. The thesis is mainly composed of three main parts. In the first part, a comprehensive suite of geotechnical laboratory tests was undertaken on CS/LS blends at various ratios (50:50, 60:40, 70:30, 80:20 and 90:10) to ascertain them as an alternative engineering fill material. The physical and mechanical tests include particle size distribution, specific gravity, water absorption, consistency, Los Angeles (LA) abrasion, modified Proctor compaction and California Bearing Ratio (CBR). Since CS is a non-plastic and durable material, the CS replacement improves soil plasticity, abrasion, CBR and swelling of the marginal lateritic soil. The results indicate that physical and mechanical properties of the 10% CS replacement blend are found to meet the requirement of local road authority for engineering fill material.

The second part investigates the density, unconfined compression strength (UCS) and durability against wetting and drying (w-d) cycles of cement stabilized LS:CS:FA blends, at various cement contents and CS:FA replacement ratios. The UCS of stabilized LS:CS:FA blends increases significantly with the CS and/or FA replacement ratio. The soaked CBR and durability against w-d cycles are also

improved by CS and/or FA replacement. Based on the specification of the Department of Highways, Thailand, the 3% C stabilized LS can be used as subbase material when blended with 30% CS replacement and as base material when blended with CS and FA at LS:CS:FA = 70:0:30 and 70:15:15. For 3% C, the 30% CS replacement can prolong the service life of stabilized subbase up to 7 cycles while LS:CS:FA = 70:0:30 and 70:15:15 can prolong the service of stabilized base up to 12 cycles. The 5% C stabilized LS/CS/FA blends with all LS:CS:FA ratios (70:30:0, 70:15:15 and 70:0:30) can resist the w-d cycles up to 12 cycles.

Last, the leachability of the heavy metals of cement stabilized LS:CS:FA blends were measured and compared with international standards. The leachate results indicate that 5% C 70%LS:15%CS:15%FA blend can be safely used in sustainable pavement applications, as the leachate heavy metal concentrations are within the acceptable range. The outcome of this study will promote the usage of waste CS and FA in an environmentally friendly pavement construction manner.



School of Construction and Infrastructure Development Student's Signature________

Academic Year 2018 Advisor's Signature________

# ACKNOWLEDGEMENT

Foremost, I would like to express my deep sense of gratitude and indebtedness to my supervisor, Professor Dr. Suksun Horpibulsuk, for his invaluable help and constant encouragement throughout the course of this research. I am most grateful to his teaching and advice not only for the research methodologies but also philosophical thoughts. I would not have achieved this far and this thesis would not have been completed without all the support from him.

Besides my advisor, I would like to express my deepest appreciation to my thesis committee: Prof. Dr. Panich Voottipruex, Asst. Prof. Runglawan Rachan, Asst. Prof. Dr.Cherdsak Suksiripattanapong, and Dr. Menglim Hoy, for their encouragement, insightful comments, and constructive questions.

Last but not least, profound gratitude is expressed to my family and my coworkers for their sacrifice and constant inspiration and encouragement throughout the course of this study.

Phuttipong Sudla

# TABLE OF CONTENTS

**Page**

# TABLE OF CONTENTS (Continued)

**Page**

# TABLE OF CONTENTS (Continued)

**Page**

# LIST OF TABLES

**Table** **Page**

# LIST OF FIGURES

# LIST OF FIGURES (Continued)

**Figure** **Page**

# LIST OF FIGURES (Continued)

**Figure** **Page**

# CHAPTER I

# INTRODUCTION

## 1.1 Rationale and background

Highway pavement generally consists of base and subbase layers, which are normally constructed from suitable materials such as natural stone, crushed rock and lateritic soil, the quality materials used for pavement structure were greatly reduced due to being used continuously. Due to high rainfall, temperature and humidity with alternative wet and dry period, nearly 60% of the soils in Thailand are lateritic soil with colors ranging from red to yellowish red. The lateritic soil mostly originates from igneous rocks and comprises well drained residues with the presence of excessive iron and aluminum oxides. The lateritic soil is found in dry flat lands and plains, throughout Thailand. This lateritic soil with suitable mechanical properties is commonly used as subbase materials in roads. However, lateritic soils are increasingly becoming scarce to source for road projects. Moreover, some lateritic soils have unfavorable properties, such as shrinkage, cracks, water sensitivity and uneven distribution. Thus, the usage of marginal lateritic soil as a pavement subbase material leads to some challenging issues. A practical improvement method for marginal lateritic soil is to blend it with suitable materials, followed by simple and cost-effective compaction to enhance interlocking between coarse-grained and fine-grained particles. This replacement method, with high quality, low-cost waste materials has significant economical and environmental values.

When no suitable materials are available, it is expensive to bring the suitable materials from distant sources. An alternative way, which is commonly used in practice, is to replace the locally available soil by suitable materials. The low cost or waste suitable material is generally considered for economical and environmental perspectives.

The disposal of solid waste is a major problem throughout the world. Therefore, a lot of attention is being directed nowadays to protecting the environment by using recycled and waste materials as alternative materials in civil engineering applications instead of disposing them in landfill sites. Increasing the use of waste and recycled materials in earthwork projects has created the necessity for a better understanding of the durability and strength performance of these materials against weathering conditions. In general, there are several scholars who have examined the utilization of different types of waste and recycled materials as a stabilizing agent to enhance the strength of weak soil (Ahmed et al., 2009, Ahmed et al., 2010, Ahmed et al., 2011a and Chen and Lin, 2009).

The waste material is considered any type of material by-product of industrial and human activity that has no lasting value (Younus et al., 2011). Escalating demand for virgin material and consequent increase in waste material production around the world are major concerns in a sustainable development, the replacement by waste materials has been recently performed (Arulrajah et al., 2014a and b), several types of waste materials; recycled crushed glass among them are commonly used in geotechnical applications such as road works (Disfani et al.,2009).

Crushed steel slag (CS) is a by-product produced during the conversion of iron ore from scrap iron to steel. Steel slags are generated during both steelmaking and refining operations. There are two separate primary steelmaking processes that produce steel slag as a by-product; (i) the basic oxygen furnace (BOF) process and (ii) the electric arc furnace (EAF) process (Irem et al., 2015). The mineralogical composition of steel slag changes with its chemical components. The common minerals in steel slag are olivine, merwinite, di-calcium silicate, tricalcium silicate, tetra-calcium aluminoferrite, di-calcium ferrite, solid compound of CaO–FeO–MnO–MgO, and free lime (Sentien et al., 2009).

Fly ash (FA) is a waste produced from the burning of coal in thermal power plants during energy production, contributing to environmental pollution. The staggering increase in the production of FA and its disposal in an environmentally friendly manner are increasingly becoming a matter of global concern. Thus, utilization of FA is strongly promoted by governments in order to minimize or ultimately eliminate the environmental hazards caused by its disposal. Efforts are underway to improve the use of fly ash in several ways with geotechnical utilization forming an important aspect of these efforts (Kaniraj and Gayathri, 2003).

In Thailand, steel slag now predominantly produced using the electric arc furnace (EAF) process. CS is a waste material that accumulates approximately 1.5 million tons per annum from total steel production in Thailand. CS has long been used in road construction as aggregates of wearing coarse asphalt concrete and as base materials (DH-S, 2007 and Ahmedzade and Sengoz, 2009; Juang et al., 2011 and Du et al., 2015). The investigation of CS as a replacement material to stabilize marginal soil has yet to be addressed. The usage of CS in marginal soil improvement for pavement applications is innovative and of interest to the industrial sectors and national road authorities, particularly as road construction requires a large volume of quality materials.

This research will enable CS traditionally destined for landfill to be used in a sustainable manner as a non-plastic replacement material for marginal lateritic soil improvement, which is significant in term of engineering, economical and environmental perspectives.

## 1.2 Research objectives

The main objectives of this study are as below:

(i) Evaluate physical and mechanical properties of lateritic soil/crushed slag (CS) blends, by mixing various ratios .

(ii) Evaluate the factors influencing strength development of marginal lateritic soil mixed crushed slag (CS) and fly ash (FA) in various proportions.

(iii) Evaluate the possibility of using CS and FA blends as a replacement material to stabilize marginal lateritic soil to be sustainable subbase and engineering fill materials.

(iv) Assess the Environmental impact on the CS and FA for sustainable subbase and engineering fill materials in pavement applications.

(v) To study the possibility to manage the waste industry to reduce environmental problems from marginal lateritic soil CS/FA blends.

## 1.3 Research methodology

### 1.3.1 Literature review

Literature review will be carried out to study the state-of-the-art of geotechnical testing such as particle size distribution, specific gravity, water absorption, consistency, Los Angeles (LA) abrasion, modified Proctor compaction, California Bearing Ratio (CBR), unconfined compression testing, durability testing and Scanning electron microscope (SEM). The topics relevant to this research was also reviewed, including general and history of slag , waste materials, raw materials, ,marginal lateritic soil, fly ash, crushed slag , characteristics and environmental aspects of slag, slag as a resource, existing research and summary of previous researchers. The sources of information are from journals, technical reports and conference papers. A summary of the literature review will be given in the thesis.

### 1.3.2 Sample collection and preparation

Lateritic soil (LS) samples will be collected from a borrow pit in Muang district, Sakonnakhon Province, Thailand. Crushed slag (CS) used in this research was obtained from Siam Steel Mill Services Co., Ltd., Chonburi Province, Thailand. Fly ash (FA) was from Mae Moh power plant in the north of Thailand. Sample preparation will be carried out in the laboratory at the Suranaree University of Technology and Bureau of Highways 3 (Sakonnakhon), Department of Highways, Thailand. CS was blended with marginal LS at various ratios (50/50, 60/40, 70/30, 80/20 and 90/10 by weight) for evaluating physical and mechanical properties of the blended material. The factors influencing strength and durability of cement stabilized LS were also investigated. The cement content was 3% and 5% C and the CS:FA ratios were 70/30/0,70/15/15 and 70/0/30 by weight.

### 1.3.3 Experimental work

The prepared samples will be tested in the laboratory. The laboratory testing is divided into two main groups as follows.

#### 1.3.3.1 Particle characteristics tests

The particle characteristics tests included the specific gravity and water absorption of coarse-grained material (AASHTO T85-70), specific gravity and water absorption of fine-grained material (AASHTO 84), Atterberg limits (AASHTO T90) and particle size distribution analysis (AASHTO T 27-70).

#### 1.3.3.2 material characteristics tests

The material characteristics tests included the Los Angeles (LA) abrasion (ASTM C131-69 and C535-69), modified compaction (AASHTO T180), California Bearing Ratio (CBR) (AASHTO T193), unconfined compression test (ASTM D 2166-85), durability(AASHTO T135) and Scanning electron microscope (SEM).

### 1.3.4 Thesis writing and presentation

All aspects of the studies mentioned will be documented and incorporated into the thesis. The thesis will reported the test results and discussion in consistent with objective of this research.



## 1.4 Scope and limitation of the study

In this study, marginal lateritic soil was collected from a borrow pit in Muang district, Sakonnakhon province, Thailand at approximately 1.5m depth from the ground surface. Crushed slag (CS) was obtained from Siam Steel Mill Services Co., Ltd., Chonburi province. Fly ash (FA) was from Mae Moh power plant in the north of

Thailand. The LS / CS ratios studied were 50/50,60/40,70/30,80/20 and 90/10 by weight for evaluating physical and mechanical properties to ascertain as the unbound pavement material. The engineering properties of stabilized material was investigated with the condition: 3% and 5% cement and CS/FA ratios of 70/30/0, 70/15/15 and 70/0/30 by weight. The factors controlling the strength development and durability will be brought out.

## 1.5 Thesis Structure

This research thesis is divided into five chapters. The first chapter includes Rationale and Background, research objectives, research methodology, scope and limitation of the study. Chapter II presents results of the literature review on general and history of slag, waste materials, raw materials, marginal lateritic soil, fly ash, crushed slag, characteristics and environmental aspects of slag, slag as a resource, existing research. Chapter III presents the marginal lateritic soil/crushed slag blends as sustainable engineering fill and subbase materials. Chapter IV discusses the environmental assessment and presents the analysis of physical, mechanical and durability improvement of cement stabilized marginal lateritic soil by crushed slag and fly ash replacement for pavement applications. Chapter V concludes the present work and suggests the topics for further study.

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# CHAPTER II

# LITERATURE REVIEW

This chapter summarizes the results of literature review on the topics relevant to this research, including general and history of slag, waste materials, raw materials, marginal lateritic soil, fly ash, crushed slag, characteristics and environmental aspects of slag, slag as a resource, existing research.

## 2.1 General and history of slag

Since 1990s, several researchers have studied the usage of recycled materials as substitute materials for geotechnical structure. In term of engineering, economic and environmental reasons, The history of slag use in road building dates back to the time of the Roman Empire, some 2000 years ago, when broken slag from the crude iron-making forges of that era were used in base construction. Roads made from Slag were first built in England in 1813 and, just seventeen years later, the first Slag road was laid in this country. By the year 1880, blocks cast of slag were in general use for street paving in both Europe and the United States. A major city under the American flag with a long history of Slag-paved streets is San Juan, Puerto Rico. Perhaps the earliest appearance of Slag in American history came with the Pilgrims. Since Slag was commonly used as ship ballast in that era, it seems likely that the Mayflower itself carried a load of this useful material. (National Slag Association). Due to the limitation of natural resources and high cost of waste disposal, recycled materials have been studied and have used in Europe. Even though Asia is rich in natural resources, the use of by-product materials has been also used. It can reduce the demand of natural aggregate, reduce carbon footprint and sustain the usage of virginal aggregate. Furthermore, quarry blasting process, crushing, transport, and stocking consumes a lot of energy and seriously ruin the environment. Then we need to break the way curb using virginal material and reuse by product materials.

The viability of recycled material in construction industry would benefit in two ways. First, the extraction of natural aggregate and waste disposal would reduce. Second, the cost of construction might be cheaper.

To increase and enhance the utilization of recycled materials, the extensive study has widely investigated the possibility of usage of waste materials for various applications. This research investigated the physical, geotechnical properties and environmental assessment of CS and FA blends as a replacement material to stabilize marginal lateritic soil to be sustainable subbase and engineering fill materials.

## 2.2 Waste materials

Waste materials are generated from various sections such as industrial, household, construction, renovation or demolition of structure, which include building of all types of both residential and nonresidential, road and bridges. Ali (2012) stated that the demolition waste materials those arise from demolition activities and generally homogenous by nature. Homogeneity increases the possibility to reuse or recycle waste materials. Construction debris is composed of brick, wood , steel, ceramic, plastic , paper old asphalt and glass.

To effectively study, the waste material is classified in various types and must be zero deleterious material, Their main components are as follows

(Portas,2004) ,Crushed Brick (CR),Concrete Aggregate and Reclaimed Asphalt Pavement (RAP).

It is possible to fine other C&D materials, but the percentage is low compared with these main components mentioned above. In general, it is not easy to evaluate C&D material composition as it varies with location, level of industrialization and construction techniques all over the countries (Portas, 2004)

Dam et al. (2011) indicated that recycled crushed concrete has been used in application ranging from placement in various paving layers (surface, base, sub-base) and as fill and embankment materials . In fact, the use of recycled materials is directly considered and earns credit in several infrastructure sustainability-rating systems that have recently been developed such as Green road and the sustainable highways self-evaluation tool.

FHWA (2004) presented that transportation agencies' experiences and research studies have shown that Recycled Concrete Aggregate (RCA) , under specific conditions , had the potential to produce strong , durable materials suitable for use in the highway infrastructure. The coarse aggregate portion of RCA has no significant adverse effects on desirable mixture proportion or workability . Recycled fine, when used , were generally limited to about 30 % of the fine- aggregate portion of the mixture.

Aggregate consumption had increased to 202 million tons by 1986 in England and Wale and was expected to rise to 226 million tons by 1995 and 245 million tons by 2005. An advisory committee on aggregate considered and concluded on future supply of aggregate for the construction industry the aggregate should be an adequate and steady supply of materials to meet needs of construction industry at minimum financial and social cost (O'Mahony, 1990)

Waste material has been defined as any type of material byproduct of human and industrial activity that has no lasting value (Tam and Tam, 2006). The growing quantities and types of waste materials, shortage of landfill spaces, and lack of natural earth materials highlight the urgency of finding innovative ways of recycling and reusing waste material (Arulrajah et al., 2011). Additionally, recycling and subsequent reuse of waste materials can reduce the demand for natural resources, which can ultimately lead to a more sustainable environment. (Disfani et al., 2011)

Kampala, A. and Horpibulsuk, S. (2013) presents basic and engineering properties of the recycled Calcium Carbide Residue (CCR) stabilized clay For the same compaction energy and CCR content, the unit weight of the recycled CCR stabilized clay is lower than that of the CCR stabilized clay because the harder attached pozzolanic products resist the compaction. The strength development and the reductionin void ratio with time confirm that the pozzolanic reaction still prevails even after remolding. This implies that the pozzolanic reaction occurs mainly on the surface of the clay–CCR clusters. The remolding of CCR stabilized clay breaks down the cementitious bonds between the CCR–clay clusters and the unreacted CCR and clay particles in the clusters are then free to interact with water. The research outcome reinforces the possibility of using the recycled CCR stabilized clay as fill and pavement materials

## 2.3 Raw materials

Theoretically, any material composed of silica and aluminium can be alkali activated.So far the investigations performed have used the following raw materials:

(a) kaolinitic clays (Barbosa et al. 2000; Davidovits 1979; Davidovits and Sawyer 1985; Rahier et al. 1996; Rahier et al. 1997);

(b) metakaolin (Alonso and Palomo 2001a; Alonso and Palomo 2001b; Davidovits 1999; Pinto 2004);

(c) fly ashes (Fernandez-Jimenez and Palomo 2005; Palomo et al. 1999);

(d) blast furnace slag (Fernandez-Jimenez et al. 1999; Purdon 1940; Wang and Scrivener 1995);

(e) mixtures of fly ashes and slag (Puertas and Fernandez-Jimenez 2003; Puertas et al. 2000);

(f) mixtures of fly ashes and metakaolin (Swanepoel and Strydom Apply Geochem 2002);

(g) mixtures of slag and metakaolin (Cheng and Chiu 2003);

(h) mixtures of slag and red mud (Zhihua et al. 2002; Zhihua et al. 2003);

( i ) mixtures of fly ashes and non-calcite materials like kaolin and stillbirth (Xuet al. 2002).

## 2.4 Marginal lateritic soil

Lateritic soils are typically formed under tropical climate experiencing alternate wet and dry seasons. They are generally acidic, have low CEC, low to moderate base saturation (Buol and Cook, 1998), dominated by kaolinite clay (80-97%).

Lateritic soil, on the other hand, is a major soil group in the tropical latitudes that is characterized by greater chemical resistance and moderately high permeability as well as less susceptibility to desiccation shrinkage (Gabas et al. 2007; Osinubi and Nwaiwu 2006, 2008). The dominant clay mineral, i.e., kaolinite minerals have fixed crystal lattices or layered structure and, therefore, exhibit only a small degree of hydration and swelling potential**.**

Lateritic soil, also known as red earth, is found in the tropics and subtropics (Maji et al., 2008). It is a residual product of a wide variety of intensive chemical weathering processes that affect rocks under strong oxidizing and leaching conditions (Ko et al., 2006). In addition, lateritic soil is enriched with aluminum silicates, aluminum hydrosilicates, iron oxides and iron hydroxides because the water leaches out the bases and the silic acid (Maji et al., 2008). Such phenomenon can be proved by the iron compound, which leads to the typical red color of the soil. Furthermore, lateritic soil is a kind of soil with abundant clay minerals that show a high affinity for immobilizing cationic or organic contaminants due to their large specific surface area and negatively charged surface (Wang et al., 2008). Additionally, developments in using lateritic soil as an adsorbent for gas cleaning and wastewater treatment have also been widely reported in recent years (Maji et al., 2008; Ko et al., 2006; Wang et al., 2008; Yu et al., 2008; Mohapatra et al., 2009). In addition, lateritic soil is known to contain high concentrations of aluminum ions (Al3þ) and ferric ions (Fe3þ), where both of these ions are the primary functional compounds in widely use chemical coagulants**.**

## 2.5 Fly ash

Fly ash is of synthetic pozzolanic character that is thought to be provided by the aluminates and amorphous silicate minerals that fly ash contains. Pozzolanic ash has the ability to react with slaked lime and water . The reaction occurring between lime and silica occurs based upon CaO–SiO2–H2O (C–S–H) formulation. Hydration reactions can also take place to formCaO–Al2O3–SiO2–H2O (C–A–S–H) phases contributing to the strength of the final product . In order to achieve that and to accelerate the reaction kinetics, curing process should be conducted under pressurized steam at 125–200 C in an auto clave..This property of fly ash provides an important advantage for the utilization of fly ash in production of construction materials.

The modification of fine grained soils with fly ash to improve their engineering properties is well recognized and widely practiced. Through stabilization, the plasticity of soil is reduced, and its compressive strength and load bearing properties are improved. Several factors such as plasticity of soil, types and amounts of fly ash, mixing and compaction methods, curing conditions, gradation and pulverization, affect the performance of stabilized soil. These issues have been previously discussed by several authors (Goktepe et al., 2008, Buhler and Cerato, 2007, Kate, 2005, Aydilek and Arora, 2004, Nalbantoglu, 2004, Kumar and Sharma, 2004, Prabakar et al., 2004, Cokca, 2001,Misra, 1998, Sivapullaiah et al., 1996, Chu and Kao, 1993, Ferguson, 1993 and Keshawarx and Dutta, 1993).

Fine grained soils with high plasticity are not desirable for use as a structural support unless their engineering properties are improved significantly in an economic manner. For many years, extensive research has been carried out on the usability of some conventional additives (e.g. lime, cement, fly ash, and cement kiln dust) and unconventional ones (e.g. chemicals, enzymes, and fibers) to improve the quality and/or stability of fine grained soils (Ghobadi et al., 2014, Cuisinier et al., 2011, Liu et al., 2011,Tastan et al., 2011, Dermatas and Meng, 2003, Sobhan and Mashnad, 2003, Cokca and Turker, 2002, Puppala, 2001 and Bell, 1996).

## 2.6 Characteristics and environmental aspects of slag

Nadine M. Piatak et al., (2015) reviews and summarized that Slag is defined as the predominantly silicate and oxide by-product derived from smelting metallic ore. The two main types of slag included in this discussion are from the primary production of ferrous ores, from iron and steel manufacturing, and from non-ferrous ores, from the recovery of base metals and some precious metals. Other non-ferrous slags include those generated from phosphate, chromite (FeCr2O4), and Al ores, among others; however, these slag types are not discussed due to the limited number of environmental studies on these slags. Slag can also be generated during the recycling of raw materials (i.e., Pb scrap recycling, alkaline battery recycling) and during the verification of municipal and nuclear waste.

Scientific interest in slag has been increasing steadily since the early 1990s. The number of slag studies that are referenced by publication .Research on slag can generally be divided into two categories: reuse and environmental effects. Studies of slag reuse fall into three main areas: the utility of slag as a construction material, metal recovery from slag, and slag use in environmental remediation applications. Many of these studies, most commonly on ferrous slags, characterize and test the geotechnical properties of slag from an engineering and construction perspective. Environmental studies, most commonly on nonferrous slag, focus on understanding the potential environmental impacts of slag deposited as waste, and concentrate on the geochemical and mineralogical properties of the material. (Nadine M. Piatak. et al., 2011).

Leaching tests, globally, there is increasing concern over the potential environmental impacts of slag. Slags were and still are widely used as construction materials and are increasingly used in environmental applications. Characterization of the environmental aspects of slag helps to evaluate its potential to release contaminants and its suitability as a potential resource. Leaching tests are used to investigate the mobility of trace elements in solid wastes and to help predict their long-term environmental behavior. There are many types of leach test procedures that vary based on the sample preparation, leachant composition, method of contact, solid-to-solution ratio, leachant renewal, temperature, contact time, and ultimately purpose, among others. The most commonly employed leaching tests can be divided into several types. First, single batch tests are agitated to maintain a homogenous mixture to aid in achieving steady state conditions. Usually crushed or sieved, samples are mixed with a leach ant solution at a specific ratio, with no leachant renewal. Single batch tests developed by the United States Environmental Protection Agency (USEPA) for regulatory compliance include the toxicity characteristic leaching procedure (TCLP), which replaced the extraction procedure toxicity test (EP-tox) in 1990, and the synthetic precipitation leaching procedure (SPLP) (USEPA, 2008). These two standard procedures use dilute acidic leachant solutions (acetic acid or acetate buffer for TCLP and EP-tox and sulfuric/nitric acid solution for SPLP) with a contact time of 18 h. The liquid-to-solid ratio is 20:1 (volume to mass) for material that is less than 9.5 mm in diameter (crushed if necessary).

## 2.7 Slag as a resource

Nadine M. Piatak et al., (2015) reviews and summarized that the majority of slag used for construction and environmental applications is from Fe and steel production. Iron and steel slag is considered a commodity and its supply and demand is summarized yearly by the United States Geological Survey (USGS). Also, several associations focus on promoting the use of slag, predominantly ferrous, such as the National Slag Association (NSA), the European Slag Association (EUROSLAG), and the Australia sian Slag Association (ASA). Slag production and reuse is a global business. In 2011, an estimated 260 to 330 million tonnes (Mt) of Fe slag and an estimated 150–220 Mt of steel slag were produced in the world; the United States produced approximately 8–9 Mt of Fe slag and approximately 9–13 Mt of steel slag in 2009 (Van Oss, 2013). By comparison, there are relatively limited data on the quantities of non-ferrous slag produced each year. According to the NSA (2009), non-ferrous slags constitute approximately 12% of total slag production. Based on ferrous slag estimates from Van Oss (2013), this would imply that approximately 50–66 Mt of non-ferrous slag were produced worldwide that year. According to Gorai et al. (2003), approximately 24.6 Mt of slag is generated each year from world production of Cu. When it comes to reuse, ferrous slag is generally considered for use in construction and environmental applications, whereas non-ferrous slag is the focus of research on reprocessing, especially historical dump material, for secondary metal recovery.

### 2.7.1 Construction materials

The majority of ferrous slag, and some non-ferrous slag, is used for construction purposes. As briefly discussed previously, the method used to cool the slag affects the physical properties of the material and influences how it is used. Although commonly vesicular, the hard and dense nature of air-cooled Fe and steel slags make them suitable for construction aggregate. Ferrous slag use in the United States in 2011,most air-cooled Fe slag is used in ready-mixed concrete, asphaltic concrete, road bases and surfaces, and fills; air-cooled steel slag has similar uses which the exception of ready-mixed concrete (Van Oss, 2013). A study by Maslehuddin et al. (2003) suggested that using steel slag aggregate in concrete produces a more durable product compared to using limestone aggregate. Most steel slag and about one-half of the Fe slag is air-cooled in the United States (Van Oss, 2013). Air-cooled slag also is used for roofing, mineral wool, as well some environmental applications discussed below. The glassy nature of granulated Fe slag gives the material hydraulic cementitious properties, which increase in strength if combined with free lime during hydration. Hadjsadok et al. (2012) found improved durability as well as less deterioration in sulfate-rich solutions for concrete and mortar containing granulated Fe slag. In 2010, approximately one-half of Fe slag was granulated and 95% of that material was used as cementitious material (Van Oss, 2013). In contrast to the United States, the majority (over two-thirds) of slag produced in Europe in 2004 was granulated; similar to the United States, the most common use of the material is in cement production (EUROSLAG, 2006). The average price per tonne for granulated Fe slag is significantly higher than for the other types of ferrous slag.

The use of some slag types, in particular from non-ferrous smelters, in construction materials has been shown to release trace elements into the environment. As previously discussed, Zn slag from the Hegeler smelter in Illinois that was used as fill for private drives, roadways and railways has contaminated residential soils with some trace elements (Weston Solutions, Inc., 2007). Laboratory and pilot scale leaching tests on road materials, mostly cements, containing Zn and Pb slag indicated that Zn and Pb are released during simulated environmental conditions and only a limited amount of some slag types can be incorporated into these materials (Barna et al., 2004; De Angelis and Medici, 2012). In contrast, laboratory leaching tests on asphalt mixes containing EAF steel slag did not release environmental significant amounts of Cr or other trace elements suggesting these materials are appropriate substitutes (Milac ic et al., 2011).

**2.7.2 Environmental applications**

The use of ferrous slag in environmental applications has been increasing with recent studies on the removal of phosphorus, nitrogen, or trace elements from solution and controlling unwanted industrial emissions. Numerous studies discuss the effectiveness of using steel slag to remove P from wastewater or agricultural runoff (Baker et al., 1998; Drizo et al., 2002, 2006; Weber et al., 2007; Bowden et al., 2009; Barca et al., 2012); another study highlighted the removal of nitrogen in constructed wetlands using steel slag (Sun et al., 2009). N.M. Piatak et al. / Applied Geochemistry 57 (2015) 236–266 259 oxides, which may increase levels of ozone, form acid rain, and acidify aquatic ecosystems, can be reduced by the addition of steel slag into cement kilns used to produce clinker by lowering the firing temperature (Srivastava et al., 2005). Ferrous slag is also used as an acid-neutralizing agent (Gahan et al., 2009) for treating acid-mine drainage resulting from coal and base-metal operations (Cravotta, 2005; Simmons et al., 2002; Ziemkiewicz and Skousen, 1999). Ferrous slags have high neutralization potentials from the dissolution of Ca silicates, oxides, and carbonates (see reactions (2) and (3)), which increases alkalinity and pH. In Ziemkiewicz and Skousen (1999), the authors suggested allowing rainfall or runoff to interact with steel slag, producing an alkaline drainage that is then allowed to infiltrate directly into an acidic waste piles or is mixed with acid-mine drainage. Another study by Simmons et al. (2002) revealed that a leach bed constructed of steel slag was effectively neutralizing acidic drainage at a coal mine site. Cravotta (2005) conducted laboratory experiments allowing acid-mine drainage to interact with steel slag and reported that the slag effectively neutralized the acidic waters. Additionally, laboratory studies indicated that steel slag effectively neutralized and adsorbed Cu from synthetic acidic drainage water (Wendling et al., 2010). Research has also focused on the use of steel slag to remove trace elements from water. A few studies investigated the removal of As or U from wastewaters, mine effluent, and synthetic solutions (Blowes et al., 2005; Kwon et al., 2008; Hanski et al., 2007; Oh et al., 2012). Another application is using steel slag to reduce carcinogenic Cr(VI) to less soluble and less toxic Cr (III) in contaminated groundwater or in synthetic solutions (Ochola and MooYoung, 2004; Hanski and Kankaala, 2009). In addition, Dimitrova (2002) experimented with using granulated Fe slag to remove Pb from solution, which is applicable to decontaminating Pb-bearing industrial wastewaters.

## 2.8 Existing Research

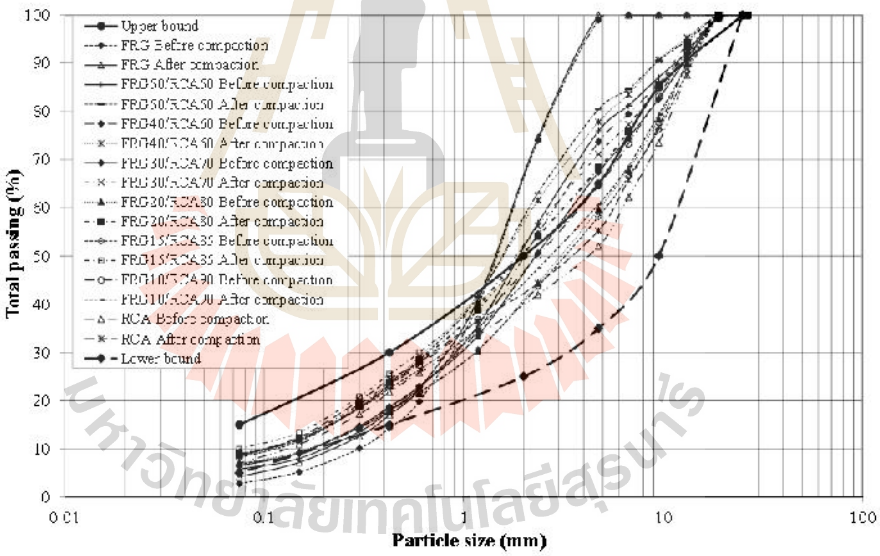
To understand the reuse potential of CS and existing practices in implementation and enforcement for achieving , the aim with an ultimate motive of engineering, environmental and economic perspectives. Since the reuse of CS is always more advantageous, if is essential to extensively study, review and suitably modified in order to establish of effective strategies and enactment of regulations of using CS materials and to promote the use of recycled products. FA has been investigated several decades ago for concrete and pavement applications.

Concrete is primarily a composition of cement, coarse aggregates, fine aggregate and water, further processed by addition of industrial products or by products for enhancing the properties. Engineers are mainly dependent on nature for obtaining the coarse and fine aggregates as well as water for the chemical reaction with cement.

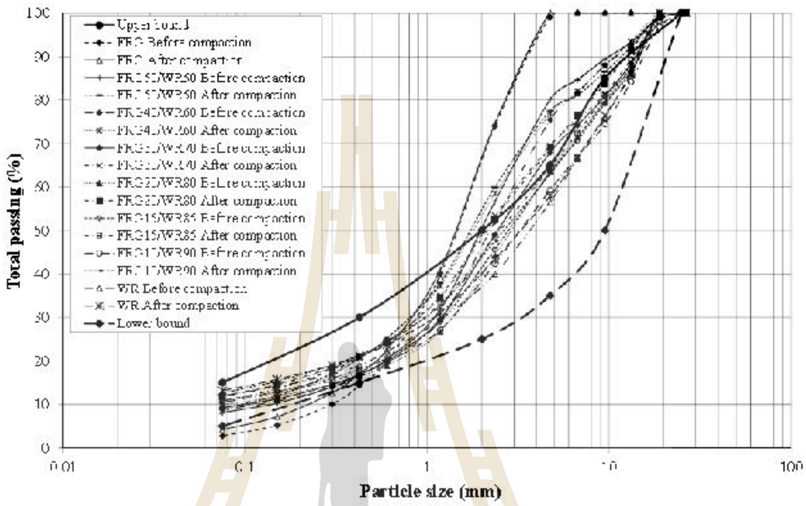
Usually the desired materials are not available locally in sufficient quantities. Foreign materials need to be brought from far off place, which increase the transportation cost . There word be economical benefit of using locally available materials construction and its performance . Somehow, the quality of locally available aggregate or borrowed aggregate would be modified by using following methohs, which result in lesser thickness of pavement layer and better pavement perfoemance.

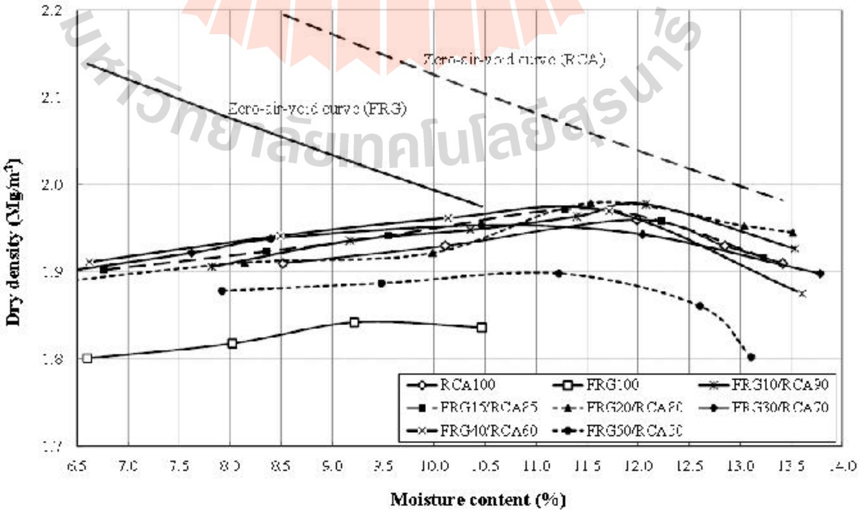
- Cement or lime stabilization
- Replacement method
- Several researchers, designers, designers, contractors have used both methods

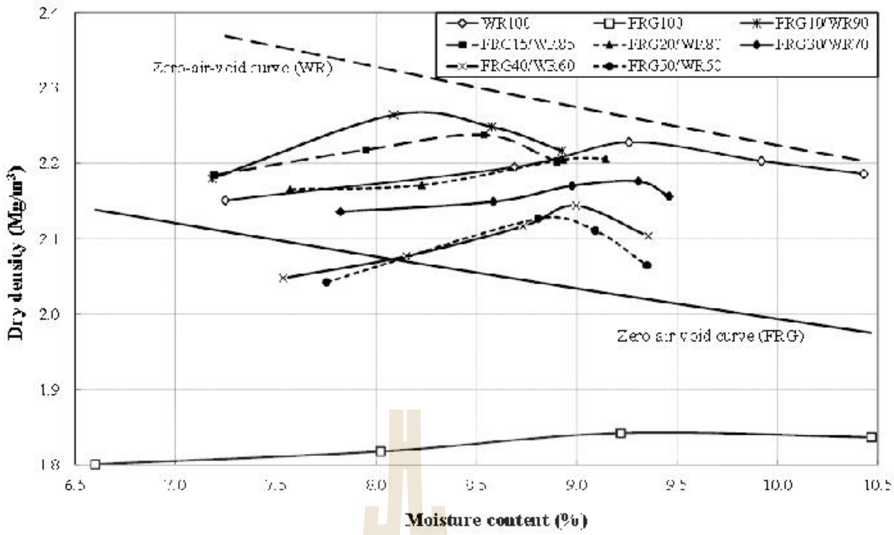
for various investigations and engineering applications. To emphasis on environmental issue, cement or lime treatment is not an environmental friendly method. Since the cement or lime production generates the carbon footprint to the



Upper bound
FRG Before compaction
FRG After compaction
FRG50/RCA50 Before compaction
FRG50/RCA50 After compaction
FRG40/RCA60 Before compaction
FRG40/RCA60 After compaction
FRG30/RCA70 Before compaction
FRG30/RCA70 After compaction
FRG20/RCA80 Before compaction
FRG20/RCA80 After compaction
FRG15/RCA85 Before compaction
FRG15/RCA85 After compaction
FRG10/RCA90 Before compaction
FRG10/RCA90 After compaction
RCA Before compaction
RCA After compaction
Lower bound
Total passing (%)
Particle size (mm)


Upper bound
FRG Before compaction
FRG15/WR85 After compaction
WR Before compaction
WR After compaction
Lower bound
Total passing (%)
Particle size (mm)
0.01
0.1
1
10
100


Zero-air-void curve (RCA)
Zero-air-void curve (FRG)
RCA100
FRG100
FRG10/RCA90
FRG15/RCA85
FRG20/RCA80
FRG30/RCA70
FRG40/RCA60
FRG50/RCA50
Dry density (Mg/m3)
Moisture content (%)



WR100
FRG100
FRG10/WR90
FRG15/WR85
FRG20/WR80
FRG30/WR70
FRG40/WR60
FRG50/WR50
Zero-air-void curve (WR)
Zero air void curve (FRG)
Dry density (Mg/m³)
Moisture content (%)

recycled aggregate concrete, to verify their utilization in civil infrastructure. Five different concrete mixes were produced; it was observed that there was no significant variation in compressive strength, split tensile strength and flexural strength of concrete while the modulus of elasticity and resistivity decreased and absorption increase with increased in percentage of recycled aggregates.

Steel slag is a byproduct from either the conversion of iron to steel in a basic oxygen furnace, or the melting of scrap to make steel in an electric arc furnace. Caijun Shi.,(2004) reviews and summarized that the production, processing, and characteristics of steel slag, and its use as a cementing component in different cementing systems. The chemical composition and cooling of molten steel slag have a great effect on the physical and chemical properties of solidified steel slag. Steel slag with high basicity and being cooled properly can exhibit cementing property.Ground steel slag has been used in several different cementing systems. The use of steel slag in these cementing systems results in some advantages over conventional cements. At the moment, most steel slag is being used as unbound aggregate for ashphalt concrete pavement in many countries. However, the use of steel slag as a cementing component should be given a priority from technical, economical, and environmental considerations.

Steel and iron slag. As stated earlier, studies on modern steel and Fe slag deposits are more numerous than on historical Fe slag but most focus on characterization and reuse. Some environmental characterization has been conducted on steel slags in the Chicago area near the border of Indiana and Illinois, USA. The geochemistry of waters and sediment in contact with some of these extensive steel slag deposits has been discussed in Bayless and Schulz (2003) and Bayless et al. (1998, 2004).

Arulrajah et al. (2013) examined the geotechnical and geoenvironmental properties of five predominant types of C&D materials for pavement application . The C&D materials tests were recycled concrete aggregate (RCCA), crushed brick (CB), waste rock (WR), reclaimed asphalt pavement (RAP). A detailed laboratory investigation was undertaken to characterize of C&D materials in term of their basic properties, shear strength parameter, resilient modulus , and permanent deformation characteristics. Table 2.3 indicates the existence of high quality aggregates in the recycled C&D materials , which contributes to higher density aggregates in the recycled C&D materials, which contributes to higher density for the coarse aggregates. LA abrasion test indicated that RCA, WR and FRG were more durable in abrasion than CB and RAP. RCA, CB and WR met the CBR requirements for usage as subbase materials.

Kavak et al.( 2011) recommended that in the earth fill works, it was important to find a materials with good compaction characteristics that provides a permanent operational solution. RLT results indicated that RCA, CB and WR performed satisfactorily at 98% CSD and at a target moisture content of 70% of the OMC. The performance of RCA, CB and WR were found to be affected by increasing the target moisture contents and the density level particularly for CB which failed at the higher target moisture contents of 80%-90%. RCA, WR were found to have much smaller permanent strain and much higher modulus than natural granular subbase, which indicated their performance as superior or equivalent to typical quarry materials.

Kumar et al.(2012) investigated the use of recycled aggregate from building waste as base course and sub-base course . Aggregate was found to be relative soft compared with conventional aggregate and can be used as-base material but not in base course and wearing course. Water absorption of RCA was found to be high as compared with conventional aggregate .

Conversely , Kavak et al. (2011) denoted that different gradaion materials provided different properties filling materials. In this case, the soil's bearing capacity and deformation under loads changes. Thus if is important to predetermine the effect of these changes in soil parameters on filling behavior. To study the effect of replacement materiais , the specimens should be prepared from gradation, which will be performed in this study.

Haoliang Huang. et al. (2006) also reported that the physico-chemical process of self-healing in blast furnace slag cement paste was investigated in this sample.With a high slag content i.e., 66% in cement paste and saturated $Ca(OH)^2$ solution as activator, it was found that the reaction products formed in cracks are composed of C\S\H, ettringite, hydrogarnet and OH–hydrotalcite.The fraction of C\S\H in the reaction products is much larger than the other minerals. Large amount of ettringite formed in cracks indicates the leaching of $SO4^{2-}$ ions from the bulk paste and consequently the recrystallization. Self-healing proceeds fast within 50 h and then slows down. According to thermodynamic modeling, when the newly formed reaction products are carbonated, the filling fraction of crack increases firstand then decreases. Lowsolubleminerals such as silica gel, gibbsite and calcite are formed. Compared to Portland cement paste, the potential of self-healing in slag cement paste is higher when the percentage of slag is high.

J. Zelic (2005) presents the results of investigation related to both the properties of the ferrochromium slag and the standard physical andmechanical properties of Portland cement concrete pavements (PCCP) made with this slag as aggregate, according to the relevant Croatian standards. Slag is formed as a liquid at 1700 -C in the manufacture of the high-carbon ferrochromium metal and, by slow cooling in the air,the slag crystallizes to give a stable CaO–MgO–Al2O3–silicate product with mechanical properties similar to basalt. With a proper selection of slag as an artificial aggregate, concrete pavements with compressive strengths, wear resistance and specific weight higher than in those from natural (limestone) aggregate in commercial Portland cement, type CEM II/B-S 42.5 (EN 197), can be made. The 28-day compressive strength of the concretes made with original unfractioned slag and with standard limestone as aggregates (w/c=0.64 and 350 kg/m3) reached the values of 57.00 MPa and 36.70 MPa, respectively. Volume stability, high volume mass, good abrasion resistance to wear and crushability make this reinforced slag concrete suitable for wearing courses of concrete pavements for traffic load classes 1 and 2 where carbonate stone material (limestone) mainly does not meet the Standard Technical Requirements for cement concrete slab pavements according to the relevant Croatian standard.

Dennis G. Grubb et al.(2013) presents the basis of these multiple lines of evidence, analyses, and the prior research involving these media (especially Grubbet al. 2010b, 2011a), arsenic leaching from the 100% DM,100% SSF, and the DM-SSF blends is extremely low to negligibleon the basis of the expected concentrations of total As in the Baltimore harbor DM (up to 100 g=kg). The fluctuating detection limits in these studies, although inconvenient, have illustrated that the behavior of As in the DM-SSF blends appears to be largely independent of the blending ratio. As little as 20% SSF blending promotes significant geotechnical improvement while maximizing the DM content such that the resulting 80=20 DM-SFF blend could be used for large-scale highway embankment construciton, port facility construction, and similar geotechnical uses. The geoenvironmental improvements are immediate and increase with aging, and perhaps more significantly, appear to exclude the formation of crystalline cementitious end-products, significant changes in moisture content, or the potential for swell (Grubb et al.2011a).

## 2.9 The new information obtained from this thesis

Research studies from the past. Found that bringing waste to be used in geotechnical engineering with extensive research. The researchers aimed to reduce the environmental impact as well. And it has a positive impact on the cost of the construction was down.The thesis attempts to study the possibility of using the crushed slag improved marginal lateritic soil for sustainable pavement applications , and then, presents the physical and mechanical properties of crushed slag and marginal lateritic soil blends. The factors influencing strength development in marginal lateritic soil/CS / fly ash. The factors are different ingredients (marginal lateritic soil/CS ratio,CS/fly ash ratio, and moisture content),specimen weights, and strength development (strength and duration). Finally,presents the durability of the marginal lateritic soil/CS / fly ash from durability test and Scanning electron microscope (SEM); which are the causes for most destructive damages in marginal lateritic soil and presents the Environmental impact. The outcome of this work would provide choices and be beneficial for marginal lateritic soil for sustainable pavement and thus lead to the reduction in the cement consumption and environmental problems, which is significant in term of engineering, economical and environmental perspectives.

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# CHAPTER III

# MARGINAL LATERITIC SOIL/CRUSHED SLAG BLENDS AS AN ENGINEERING FILL MATERIAL

## 3.1 Introduction

Highway pavement generally consists of base, subbase and engineering fill layers, which are typically constructed from suitable materials such as crushed rock and lateritic soil (LS). Due to high rainfall, temperature and humidity with alternative wet and dry period, nearly 60% of the soils in Thailand are LS with colors ranging from red to yellowish red. LS mostly originate from igneous rocks and comprises well drained residues with the presence of excessive iron and aluminum oxides. LS is found in dry flat plains, throughout Thailand. This LS with suitable mechanical properties is commonly used as subbase and engineering fill materials in roads. LS consists of coarse- and fine-grained particles, and are increasingly becoming scarce to source for road projects. LS with a high percentage of fine-grained particles has some unfavorable properties, which result in shrinkage during dry seasons and swelling during wet seasons and exacerbated with its water sensitivity and uneven distribution, are often only considered appropriate for use as subgrade materials (Phummiphan et al., 2015 and 2016; and Suebsuk et al., 2017). The usage of marginal LS as a pavement subbase and engineering fill materials therefore leads to some challenging issues, which this research seeks to address. A practical improvement method for marginal LS is to blend it with suitable materials, followed by simple and cost-effective compaction to enhance interlocking between coarse-grained and fine-grained particles (Horpibulsuk et al., 2008, 2009 and Bo et al., 2014). Compacting in-situ soil mixed with alternative virgin aggregates is a common and economical option for a modification of LS to achieve the adequate mechanical properties for roadway construction. (Chinkulkijniwat and Horpibulsuk, 2012; and Horpibulsuk et al., 2006, 2013b). This replacement method is more considered as a cost-effective and environmental-friendly technique if the recycled and/or waste materials are used as an alternative material to substitute the virgin aggregates. Hence, it can reduce the cost of the roadway construction and give the positive environment impacts.

Generally, wastes are considered as a one-life cycle material, which has no lasting value or discarded after its utilization. A large quantity of waste materials is widely known as a municipality solid waste that is generated by industrial, human and commercial activities. Recycling is a method of converting wastes into new things or materials. Without proper recycling process, the wastes are undesirable or unusable debris that dispose on the landfill, which pertaining to the environmental problem; i.e., some waste contains metal or toxic compounds that can contaminate the soil, surface and ground water.

In recent decades, the innovative researches worked on converting the soil wastes into a source of material that applicable to substitute virgin aggregates in pavement applications have got an enormous endorsement from diverse research panels, including government consignment, commercial industrial and education sectors. Steel slag has been used to improve a poor engineering properties of soil and reported as a low-cost soil modification technique (Akinwumi, 2014). The physical and mechanical properties of the blend were characterized by geotechnical laboratory experimental program, including sieve analysis, consistency limits, specific gravity, compaction, California bearing ratio (CBR), unconfined compressive strength (UCS) test. Similar study has been conducted by Yadu et al. (2013) to investigate the physical and strength properties of soft soil and slag mixture. It indicates that the utilization of optimum amount of slag can reduce the free swelling and lead to improve the soaked CBR and UCS.

The scientific and practical methodologies and outcomes from the previous researchers have been reviewed as literature in this research in order to make a new illuminating study on a cleaner production as well as to assure that waste materials can be mixed with soil as an intuitive practitioner interface technique in pavement applications.

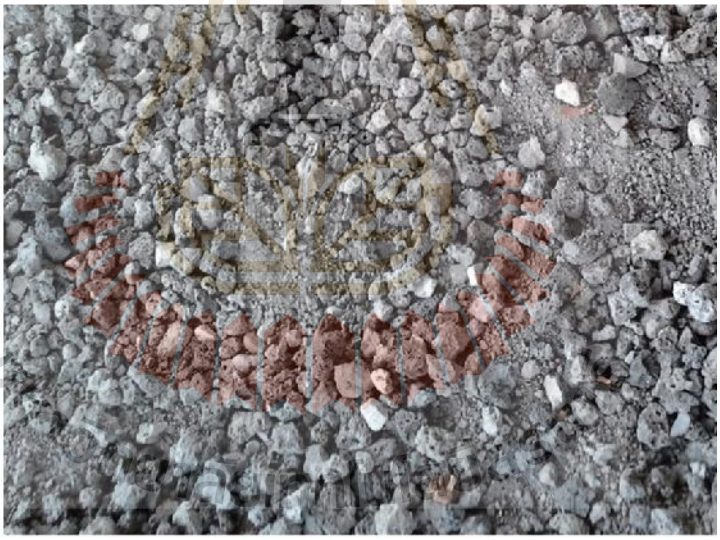
Crushed steel slag (CS) is a by-product produced during the conversion of iron ore from scrap iron to steel. Steel slags are generated during both steelmaking and refining operations. There are two separate primary steelmaking processes that produce steel slag as a by-product; (i) the basic oxygen furnace (BOF) process and (ii) the electric arc furnace (EAF) process (Lizarazo-Marriaga et al., 2011; Maghool et al., 2017). The mineralogical composition of steel slag changes with its chemical components. The common minerals in steel slag are olivine, merwinite, di-calcium silicate, tricalcium silicate, tetra-calcium aluminoferrite, di-calcium ferrite, solid compound of CaO–FeO–MnO–MgO, and free lime (Sentien et al., 2009).

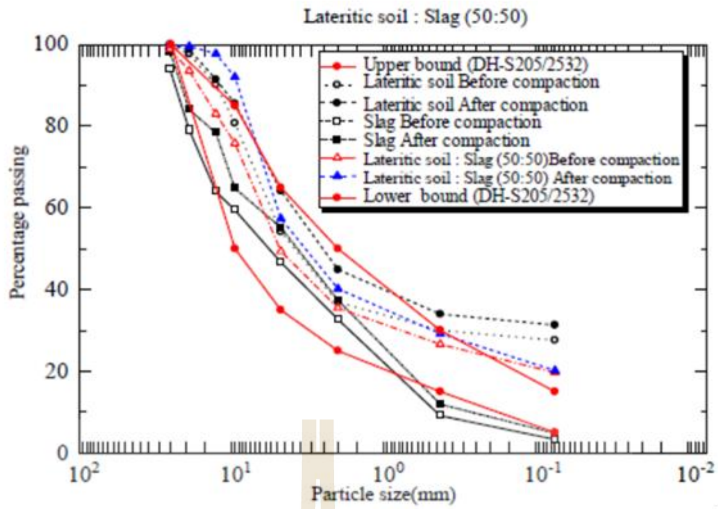
In Thailand, steel slag is currently predominantly produced using the electric arc furnace (EAF) process. CS is a waste material that accumulates approximately 1.5 million tons per annum from total steel production in Thailand. CS has long been used in road construction as aggregates of wearing coarse asphalt concrete and as base materials (Manso et al., 2005; Ahmedzade and Sengoz, 2009; Malasavage et al., 2012; Shahu et al., 2013; Tripathi et al., 2013; Yildirim et al., 2013; Du et al., 2015 and Maghool et al., 2016). CS can also be used for soil improvement such as the usage of basic oxygen steel slag fines for soil and dredge material stabilization (Poh et al., 2006, Nicholas et al., 2012 and Dennis et al.,2013) and the usage of ladle furnace slag as an embankment material (Montenegro et al., 2013). Even though there is available research on CS improved soil, the evaluation of CS as a replacement material to stabilize marginal soil and the assessment of mechanical properties such as California bearing ratio and swelling have yet to be satisfactorily addressed. Soil is a type of organic matter comprises of variable complex chemical and physical properties and it is varied based on geological structure. Thus, an explicit study on physical and mechanical of the local soil improvement is required prior to utilize in pavement application. The usage of CS in marginal soil improvement for pavement applications is innovative and of interest to the industrial sectors and national road authorities, particularly as road construction requires a large volume of quality materials.

This research aims to investigate the physical and mechanical properties of marginal LS/CS blends at various replacement ratios to evaluate them as an engineering fill material. Since CS has a higher unit weight than LS, the more CS replacement results in the higher bearing stress on subgrade and foundation. To minimize the unit weight of the stabilized material, the CS replacement should be within 50% of the marginal soil. Furthermore, a greater CS replacement content is not considered to be economical, due to the high haulage cost especially for the construction site far away from CS sources. This research will enable CS traditionally destined for landfill to be used as a non-plastic replacement material for marginal LS improvement, which is significant in term of engineering, economical and environmental perspectives.

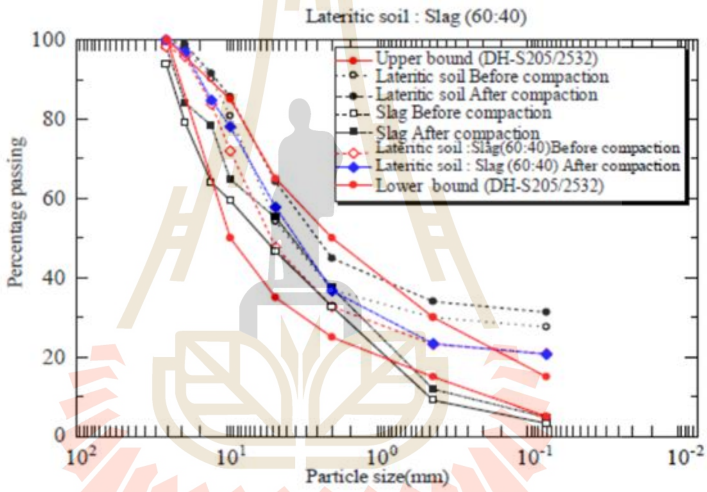
## 3.2 Materials And Methods

Marginal LS was collected from a borrow pit in Muang district, Sakonnakhon province, Thailand (Figure 3.1a) at approximately 1.5 m depth from the ground surface. The LS was composed of 21.7% fine-grained particles, and 78.3% coarse-grained particles in which 47.3% is gravel and 31.0% is sand. The specific gravity of coarse-grained particles is 2.67 and liquid and plastic limits are 40.7% and 20.9%, respectively. According to the Unified Soil Classification System (USCS), this LS is classified as clayey gravel (GC). The grain size distribution curve is shown in Figure 3.2 and physical properties are summarized in Table 3.1. By comparing with the specification for sub-base and engineering fill materials (DS-205/2532) from the Department of Highways, this LS does not meet the standards and requires an improvement in mechanical properties to enable it to be used as engineering fill material.

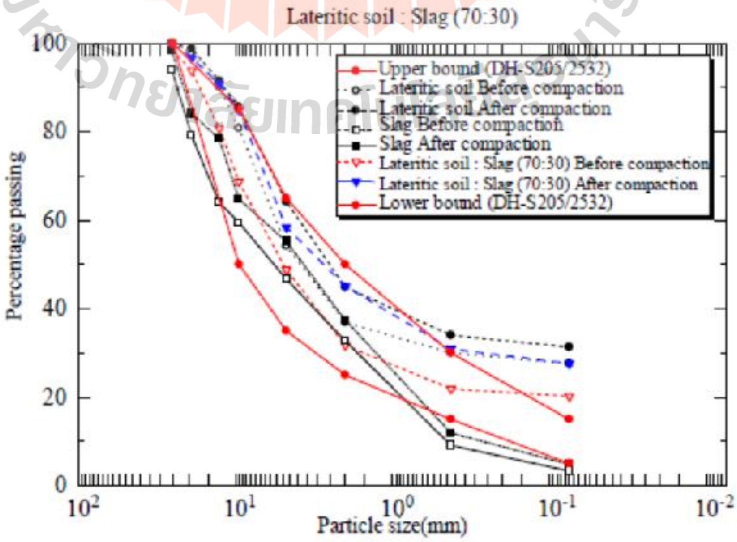




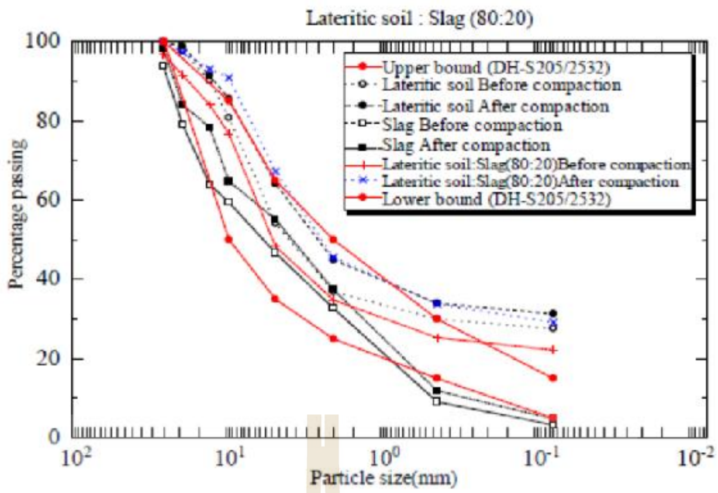
Lateritic soil : Slag (50:50)
Upper bound (DH-S205/2532)
Lateritic soil Before compaction
Lateritic soil After compaction
Slag Before compaction
Slag After compaction
Lateritic soil : Slag (50:50)Before compaction
Lateritic soil : Slag (50:50) After compaction
Lower bound (DH-S205/2532)
Percentage passing
Particle size(mm)

Lateritic soil : Slag (60:40)
Upper bound (DH-S205/2532)
Lateritic soil Before compaction
Lateritic soil After compaction
Slag Before compaction
Slag After compaction
Lateritic soil :Slag(60:40)Before compaction
Lateritic soil : Slag (60:40) After compaction
Lower bound (DH-S205/2532)
Percentage passing
Particle size(mm)

Lateritic soil : Slag (70:30)
Upper bound (DH-S205/2532)
Lateritic soil Before compaction
Lateritic soil After compaction
Slag Before compaction
Slag After compaction
Lateritic soil : Slag (70:30) Before compaction
Lateritic soil : Slag (70:30) After compaction
Lower bound (DH-S205/2532)
Percentage passing
Particle size(mm)


Lateritic soil : Slag (80:20)
Upper bound (DH-S205/2532)
Lateritic soil Before compaction
Lateritic soil After compaction
Slag Before compaction
Slag After compaction
Lateritic soil:Slag(80:20)Before compaction
Lateritic soil:Slag(80:20)After compaction
Lower bound (DH-S205/2532)
Percentage passing
Particle size(mm)

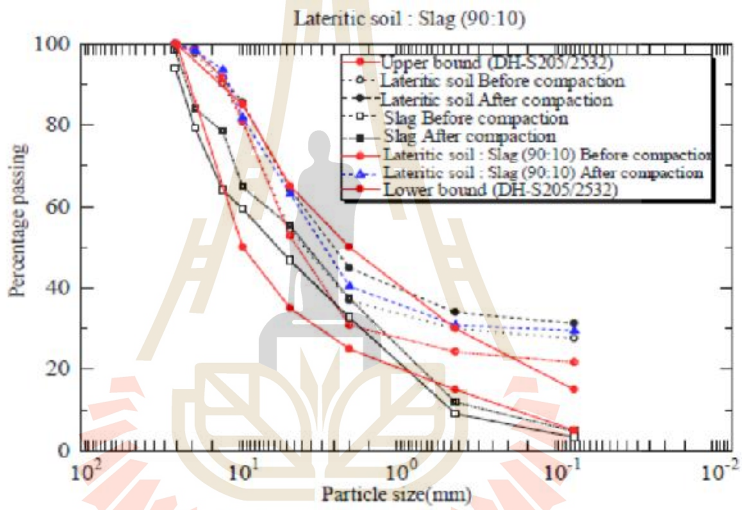

Lateritic soil : Slag (90:10)
Upper bound (DH-S205/2532)
Lateritic soil Before compaction
Lateritic soil After compaction
Slag Before compaction
Slag After compaction
Lateritic soil : Slag (90:10) Before compaction
Lateritic soil : Slag (90:10) After compaction
Lower bound (DH-S205/2532)
Percentage passing
Particle size(mm)

**Table 3.1** Physical properties of LS/CS blends.

| Sample Description | CS | Lateritic Soil : CS | | | | | LS | Remark |
|---|---|---|---|---|---|---|---|---|
| | | 50:50 | 60:40 | 70:30 | 80:20 | 90:10 | | |
| Bulk specific gravity Coarse-grained | 3.35 | 2.92 | 2.89 | 2.77 | 2.76 | 2.70 | 2.67 | AASHTO T85-70 |
| Bulk specific gravity Fine-grained | 3.54 | 3.20 | 3.21 | 3.21 | 3.22 | 3.21 | 3.03 | AASHTO 84 |
| Average specific gravity Coarse-Fine grained | 3.44 | 3.06 | 3.05 | 2.99 | 2.99 | 2.95 | 2.85 | |
| Apparent specific gravity Coarse-grained | 3.51 | 3.25 | 3.30 | 3.23 | 3.23 | 3.19 | 3.18 | AASHTO T85-70 |
| Apparent specific gravity Fine-grained | 4.26 | 3.72 | 3.71 | 3.72 | 3.73 | 3.70 | 3.47 | AASHTO 84 |
| Water absorption Coarse-grained | 1.34 | 3.41 | 4.34 | 5.06 | 5.27 | 5.68 | 5.95 | AASHTO T85-70 |
| Water absorption Fine- grained (%) | 4.79 | 4.30 | 4.26 | 4.28 | 4.20 | 4.18 | 4.19 | AASHTO 84 |
| LA abrasion value (%) | 17.2 | 42.3 | 46.2 | 47.58 | 48.2 | 51.18 | 58.1 | ASTM C131 ,C535 |
| LL (%) | - | 30.3 | 31.9 | 32.7 | 37.8 | 38.6 | 40.7 | AASHTO T90 |
| PL (%) | - | 20.2 | 21.7 | 21.2 | 20.4 | 20.4 | 20.9 | AASHTO T90 |
| PI (%) | - | 10.1 | 10.2 | 11.5 | 17.4 | 18.1 | 19.8 | |
| $D_{10}$ (mm) | 0.45 | - | - | - | - | - | - | |
| $D_{30}$ (mm) | 1.75 | 0.76 | 1.35 | 1.50 | 0.90 | 0.37 | 1.80 | |
| $D_{50}$ (mm) | 5.50 | 3.70 | 5.10 | 4.75 | 4.90 | 4.00 | 4.50 | |
| $D_{60}$ (mm) | 9.5 | 5.48 | 6.70 | 6.90 | 6.10 | 5.50 | 5.50 | |
| $C_u$ | 21.11 | - | - | - | - | - | - | |
| $C_C$ | 0.72 | - | - | - | - | - | - | |
| Gravel size content (%) | 53.3 | 50.6 | 50.3 | 49.2 | 48.5 | 48.0 | 47.3 | Retained #4 |
| Sand size content (%) | 43.4 | 32.0 | 31.2 | 31.6 | 31.0 | 31.6 | 31.0 | Passed#4-Retain#200 |
| Fines size content (%) | 3.3 | 17.4 | 18.5 | 19.2 | 20.5 | 20.4 | 21.7 | Passed#200 |
| Classification-USCS | GP | GC | GC | GC | GC | GC | GC | |

The LS:CS contents studied were in proportions of 50:50, 60:40, 70:30, 80:20 and 90:10 based on weight. **Figure 3.1c** shows the photo of LS/CS blend at 50% CS replacement. The laboratory evaluation program on marginal LS/CS blends includes: (i) specific gravity, (ii) water absorption, (iii) Atterberg limit, (iv) modified Proctor compaction, (v) Los Angeles (LA) abrasion, and (vi) California Bearing Ratio (CBR) tests. All tests were undertaken following relevant American Association of State

Highway and Transportation Officials (AASHTO) and American Society for Testing and Materials (ASTM).

Specific gravity and water absorption tests of coarse-grained particles were performed in accordance with AASHTO T 85-70. For fine-grained particles, the specific gravity and water absorption tests were performed in accordance with AASHTO T 84. Atterberg limit tests were performed in accordance with AASHTO T 90. Particle size distribution analysis tests were performed in accordance with AASHTO T 27-70. Particle size distribution analysis and Atterberg tests were conducted on samples both before and after modified compaction tests to investigate the particle breakage due to compaction.

Based on the specification for pavement material construction by the Department of Highways and Department of Rural Roads of Thailand, base, subbase and engineering fill materials must be compacted under modified compactive energy while the subgrade must be compacted under standard compactive energy. Modified compaction tests were then conducted on the LS/CS blends by following the AASHTO T 180 to determine the maximum dry density (MDD) and optimum moisture content (OMC) of the LS/CS blends. LA abrasion test was performed in accordance with ASTM C131-69 and C535-69. LA abrasion test is the most widely specified test for evaluating the resistance of aggregates to abrasion and impact forces (Papagiannakis and Masad, 2007).

California bearing ratio (CBR) and swelling test method were in accordance with AASHTO T 1993. The CBR and swelling tests were carried out on blends subjected to modified Proctor compaction effort at the optimum water content and soaked for 4 days to simulate the worst-case scenario whereby the soil is fully saturated (Arulrajah et al. 2014b). For each CS replacement ratio, at least five samples

were tested under the same conditions to ensure consistency of the results. In most cases, the results under the same testing condition were reproducible with low mean standard deviation, *SD* ($SD/\bar{x}$ < 10%, where $\bar{x}$ is mean strength value).

## 3.3 Results And Discussion

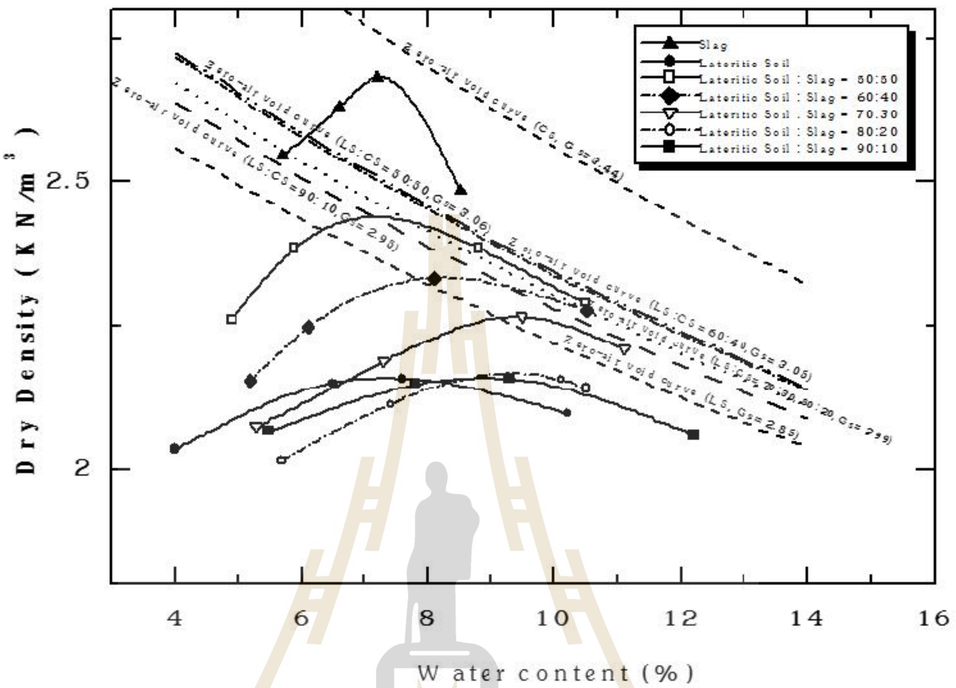
### 3.3.1 Physical Properties

The physical properties required for compacted materials according to Department of Highways, Thailand include water absorption, gradation, plasticity and Los Angles abrasion. The role of CS replacement on improving physical properties and the comparison of improved physical properties and requirement of Department of Highways is presented in this section. **Table 3.1** presents the physical properties of LS/CS blends at various CS replacement ratios. The relevant international standards for water absorption specify a different testing method to be followed for coarse-grained blends (AASHTO T 85-70) and for fine-grained blends (AASHTO T 84). The water absorption of the coarse-grained blends is determined from the particles of greater than 0.075 mm while the water absorption of the fine-grained blends is determined from the particles of smaller than 0.075 mm. The water absorption of coarse- and fine-grained CS are significantly different, indicating the fine-grained CS has higher water absorption potential. The same is not true for LS whose water

**Table 3.2** Mechanical properties of compacted LS/CS blends

| Sample Description | CS | Lateritic Soil : CS | | | | | Lateritic Soil | Remark |
|---|---|---|---|---|---|---|---|---|
| | | 50:50 | 60:40 | 70:30 | 80:20 | 90:10 | | |
| Compaction (Modified):Max Dry Density (KN/m$^3$) | 26.9 | 24.3 | 23.4 | 22.6 | 21.7 | 21.6 | 21.6 | AASHTO T180 |
| Compaction (Modified):OMC (%) | 7.25 | 7.25 | 8.25 | 9.65 | 9.40 | 8.70 | 7.60 | AASHTO T180 |
| California Bearing Ratio (Soaked 4 days) (%) | 95 | 45 | 34 | 31 | 26.5 | 19 | 9.3 | AASHTO T193 |
| Swell (Soaked 4 days) (%) | 0 | 2.26 | 2.97 | 3.87 | 4.41 | 5.04 | 6.40 | AASHTO T193 |
| LL (%) | - | 32.5 | 33.9 | 37.5 | 39.4 | 39.4 | 45.6 | AASHTO T90 |
| PL (%) | - | 21.2 | 22.2 | 27.1 | 27.3 | 23.2 | 24.6 | AASHTO T90 |
| PI (%) | - | 11.3 | 11.7 | 10.4 | 12.1 | 16.2 | 21.0 | |
| $D_{10}$ (mm) | 0.27 | - | - | - | - | - | - | |
| $D_{30}$ (mm) | 1.30 | 0.45 | 0.92 | 0.29 | 0.09 | 0.18 | - | |
| $D_{50}$ (mm) | 3.80 | 3.25 | 3.45 | 2.75 | 2.40 | 2.80 | 2.50 | |
| $D_{60}$ (mm) | 7.00 | 4.95 | 5.10 | 4.80 | 3.50 | 4.25 | 4.00 | |
| ($D_{50}$(before)- $D_{50}$(after))/D50 (before) | 0.31 | 0.12 | 0.32 | 0.42 | 0.51 | 0.30 | 0.44 | |
| $C_u$ | 25.92 | - | - | - | - | - | - | |
| $C_C$ | 0.89 | - | - | - | - | - | - | |
| Gravel size content (%) | 44.8 | 42.6 | 42.2 | 41.6 | 39.7 | 36.9 | 35.8 | Retained #4 |
| Sand size content (%) | 50.4 | 37.2 | 37.1 | 30.8 | 31.1 | 33.6 | 32.9 | Passed#4-Retain#200 |
| Fines size content (%) | 4.8 | 20.2 | 20.7 | 27.6 | 29.2 | 29.5 | 31.3 | Passed#200 |
| Classification-USCS | SP | GC | GC | GM | GM | GC | GC | |

absorption is similar for both coarse- and fine-grained LS. The water absorption of coarse-grained CS (= 1.34%) is approximately 4.4 times lower than that of coarse-grained LS (= 5.95%) while the water absorption of fine-grained CS (= 4.79%) is slightly higher than that for fine-grained LS (= 4.19%). The lower water absorption of coarse-grained CS can be attributed to steel having lower water absorption potential than soil in nature. Since the water absorption of the predominantly coarse-grained CS is very low, the water absorption of the CS is significantly lower than that of LS. As such, the water absorption values of coarse-grained LS/CS blends decrease with



Slag
Lateritic Soil
Lateritic Soil : Slag - 50:50
Lateritic Soil : Slag - 60:40
Lateritic Soil : Slag - 70:30
Lateritic Soil : Slag - 80:20
Lateritic Soil : Slag - 90:10
Zero-air void curve (CS, Gs=4.44)
Zero-air void curve (LS:CS=50:50, Gs=3.06)
Zero-air void curve (LS:CS=90:10, Gs=2.95)
Zero-air void curve (LS:CS=60:40, Gs=3.05)
Zero-air void curve (LS, Gs=2.85)
2.5
2
4
6
8
10
12
14
16
Dry Density (KN/m³)
Water content (%)

Liquid limit (LL) and plasticity index (PI) are the important factors that help engineers or pavement designers to understand the consistency or plasticity of a soil that associate to the strength and deformation of the soil materials. As CS is classified as a non-plastic, coarse-grained material, when it is blended with LS, it reduces the plasticity of the marginal LS as evident in **Table 3.1**. The LL and PI values of the marginal LS are gradually decrease from 40.7 to 30.3 and from 19.8 to 10.1, respectively when the CS replacements increase from 0% to 50%. It demonstrates that the LL and PI values of LS/CS blends met the consistency limits for subbase material (LL ≤ 35 and PI ≤ 11) specified by the Department of Highway, Thailand (DH-S, 1996). Moreover, with a relatively low LA abrasion of CS = 17.2% compared with that of LS = 58.1%, the CS replacement significantly improves the LA abrasion of the blends. The LA abrasion of LS decreases from 58.1% (for 0% CS replacement) to 42.3% (for 50% CS replacement). The LS/CS blends for all CS replacement proportions met the LA abrasion requirements of < 60%, specified for subbase and engineering fill materials. The particle size distribution of the LS/CS blend was not within the limits specified for base and sub-base materials, however met the requirements for an engineering fill material.



### 3.3.2 Compaction Behavior

The modified compaction test results in **Table 3.2** and **Figure 3.3** show that the blends at various CS replacement ratios exhibit a bell-shaped compaction pattern, typical for geo-materials (Horpibulsuk et al., 2008 and 2009). The compactive effort forces the soil and CS particles move into the available pores by the expulsion of air with the assistance of water lubrication. In other word, air is expelled by the compative effort and water facilitates the rearrangement of the soil and CS particles into a denser configuration. As a result, the dry density increase until the maximum dry density (MDD) is achieved at the optimum moisture content (OMC). After the attainment of the MDD, the compactive effort cannot expel more air at water contents above the OMC and the excessive water fills the pores and displaces soil particles, thus decreasing the number of soil gains per unit volume of soil. Consequently, the dry density decreases. The compaction curve for CS is more sensitive to water content than that of LS. The MDD value of the compacted CS is 26.9 kN/m$^3$, and is relatively higher than that MDD value = 21.6 kN/m$^3$ of the compacted LS, while the OMC = 7.25% of the compacted CS is slightly lower than that OMC = 7.6% of the compacted LS. The higher MDD of CS is due to the higher specific gravity. The bulk specific gravity of coarse-grained particles of CS and LS are 3.35 and 2.67, respectively. The MDD values of LS/CS blends are between those of the LS and CS, which are 21.6 kN/m$^3$, 21.7 kN/m$^3$, 22.6 kN/m$^3$, 23.4 kN/m$^3$ and 24.3 kN/m$^3$ for 10%, 20%, 30%, 40%, and 50% CS replacement, respectively. It is evident that the CS replacement significantly increases the MDD of the blends from 21.6 kN/m$^3$ (for 0% CS replacement) to 24.3 kN/m$^3$ (for 50% CS replacement). The increase in CS replacement increases not only the density but also the water sensitivity; i.e., distinct peak is detected. The compacted characteristics and the MDD values of LS/CS blends are insignificant different even with the CS replacement up to 20%. However, the significant increase in MDD is clearly noted when the CS replacement ratio is greater than 20%. The variation of OMC of the blends with CS replacement is in a narrow band (from 7.6% to 9.65%) as the OMC values of LS and CS are almost similar. The OMC values of the LS/CS blends are 8.7%, 9.4%, 9.65%, 8.25%, and 7.25% for 10%, 20%, 30%, 40%, 50% CS replacement, respectively.

The effect of compaction effort on the particle breakage of LS, CS, and LS/CS blends is shown in **Figures 3.2**. This effect is notably significant for LS particularly for particles smaller than 10 mm, while the particle breakage for CS is found to be insignificant. By comparing **Tables 3.1** and **3.2**, it is apparent that after compaction, the contents of gravel-sized and sand-sized particles of LS decreased due to the breakage of large particles by the compaction effort, resulting in the increase of the silt-sized and clay-sized particles; i.e., the coarse (gravel and sand) content decreases from 78.3% to 68.7% while the fine (silt and clay) content increases from 21.7% to 31.3% after compaction of LS. Although the compaction effort causes the particle breakage of CS, it is noted that the coarse content of CS decreases slightly from 96.7% to 95.2%. It is consistency that the fine content of CS increase slightly from 3.3% to 4.8% after compaction. Furthermore, the particle breakage of CS decreases the gravel size contents about 8.5% and results in increasing about 7% of sand size content and only 1.5% of the fine size content. Consequently, the soil classification of CS changes from poorly-graded gravel (GP) to poorly-graded sands (SP). In contrast to CS, the particles breakage of LS decreases the gravel size contents about 11.5%; however, it raises only 1.9% of sand size contents but 9.6% of fine size content. This is evident to indicate that the particle strength of CS is higher than LS. Therefore, due to the high particle strength of CS, CS replacement notably prevents the breakage of the coarse aggregate of LS and hence the minimal reduction of the fine content. The soil classification of the blends before and after compaction remains the same for 10% CS replacement.

**Table 3.3** Mechanical properties of LS/CS blends compared with specification from Department of Highways, Thailand.

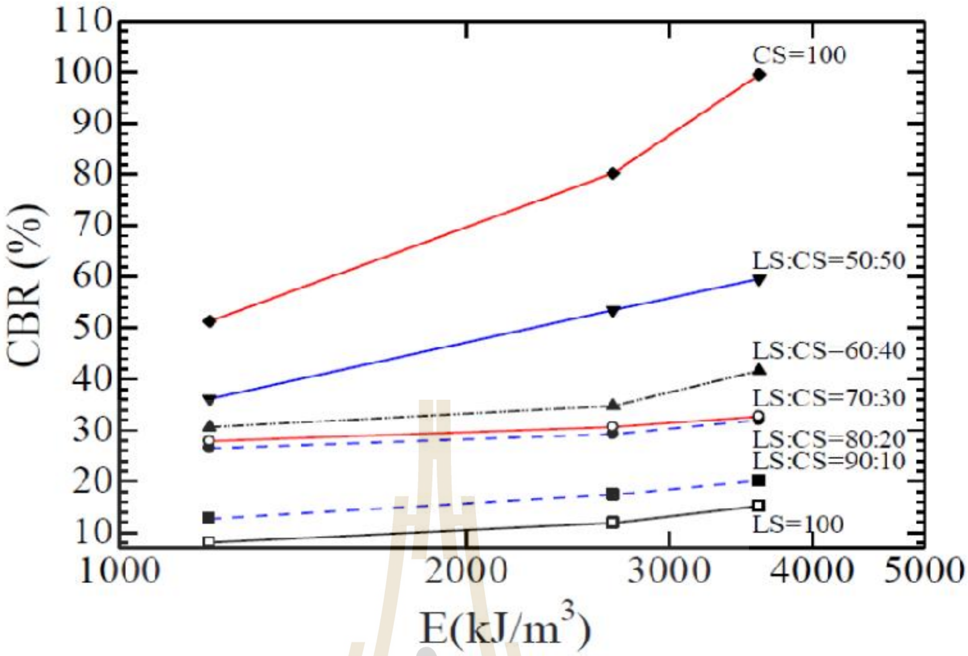
| Sample Description | Base Material (DH-S210/2547) | Sub-base Material (DH-S205/2532) | Engineering Fill Material (DH-S208/2532) | CS | Lateritic Soil : CS | | | | | Lateritic Soil |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 50:50 | 60:40 | 70:30 | 80:20 | 90:10 | |
| LA abrasion value (%) | ≤ 40 | ≤ 60 | ≤ 60 | 17.2 | 42.3 | 46.2 | 47.6 | 48.2 | 51.2 | 58.1 |
| California Bearing Ratio (%) | ≥80 | ≥25 | ≥10 | 95.0 | 45.0 | 34.0 | 31.0 | 26.5 | 19.0 | 9.3 |
| Swell (%) | ≤0.5 | ≤4 | ≤3 | 0 | 2.3 | 3.0 | 3.9 | 4.4 | 5.0 | 6.40 |
| LL (%) | ≤25 | ≤35 | ≤40 | - | 30.3 | 31.9 | 32.7 | 37.8 | 38.6 | 40.7 |
| PI (%) | ≤4 | ≤11 | ≤20 | - | 10.1 | 10.2 | 11.5 | 17.4 | 18.1 | 19.8 |

### 3.3.3 California Bearing Ratio and Swelling

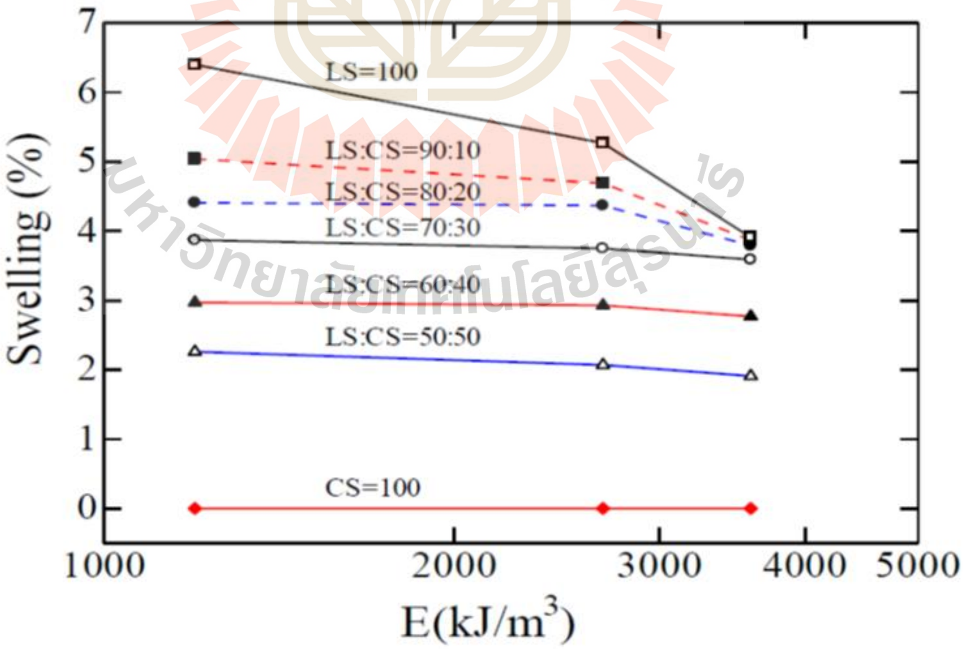
The particle breakage causes an increase in fine content and hence the increase in liquid limit and plastic limit of LS and LS/CS blends after compaction. The LL and PI values of the LS after compaction increases from 40.7% to 45.6% and from 19.8% to 21.0%, respectively. Since the mechanical properties of the compacted materials are governed by the after-compaction physical properties, increased particle breakage results in poorer mechanical properties. In other words, CS replacement prevents particle breakage and hence the improvement of mechanical properties, which are soaked CBR and swelling.

Generally, bearing capacity or CBR and swelling of compacted materials are controlled by the fines content. Higher fines content causes the higher water holding capacity in which the water acts as a lubricant among the soil particles and results in lower bearing capacity or CBR. The test results for CBR and swelling at modified Proctor energy of the blends are shown in **Table 3.3**. The increase of CS replacement in LS/CS blends can reduce the fine content and water holding capacity and leads to improve the CBR values. It is noted that the highest soaked CBR value of 95% is found for CS, while the lowest value of 9.3% is found for LS. In addition, the CBR values of LS/CS blends increase with increasing CS replacement; i.e., the CBR value of LS/CS ratio of 90:10, 80:20, 70:30, 60:40, and 50:50 is 19.0%, 26.5%, 3.10%, and 45.0%, respectively. Generally, higher swelling is associated with higher water absorption of fine content. The water absorption of LS decreases with increasing CS replacement (**Table 3.1**), resulting in decreased swelling. The swelling value at modified Proctor energy for 4 days soaked of CS is nominal. It is evident as shown in **Table 3.3** that the swelling value of LS/CS blends gradually decreases from 5.0% to 2.3% as CS replacement increases from 10% to 50%, respectively.

**Figure 3.4** shows the soaked CBR values at different compaction energy levels for various CS replacement ratios in semi-logarithm function. The results indicate that for a given CS replacement ratio, the soaked CBR value increased significantly with increased compaction energy ($E$). For a given compaction energy, the soaked CBR increases with an increased CS replacement proportion; i.e., the 100% CS replacement exhibits the highest soaked CBR for all $E$ values. The slope of all the blends increases with an increasing CS replacement ratio, indicating that the CS replacement improves the energy-sensitivity of the blends. With higher CS replacement, the soaked CBR development with compaction energy is larger.



CBR (%)
E(kJ/m³)
CS=100
LS:CS=50:50
LS:CS=60:40
LS:CS=70:30
LS:CS=80:20
LS:CS=90:10
LS=100

Swelling (%)
E(kJ/m³)
LS=100
LS:CS=90:10
LS:CS=80:20
LS:CS=70:30
LS:CS=60:40
LS:CS=50:50
CS=100

**Figure 3.5** shows the swelling versus logarithm of *E* relationship for various CS replacement ratios. Unlike the soaked CBR versus logarithm of *E* relationship, two types of relationship are found: bi-linear and linear. The bi-linear relationship is found when the CS replacement is less than 30% and the slope change is found at $E$ = 2681 kJ/m$^3$ (modified Proctor energy). Steeper slopes are observed at lower CS replacement ratios, indicating that the compaction energy plays a significant role on the swelling reduction when CS is lower than 30%, particularly when $E >$ 2681 kJ/m$^3$. By replacing LS with CS, the swelling is reduced as the CS replacement ratio increases. It is evident that both slopes of all the blends decrease with increasing of CS replacement ratio.

In contrast to the previous research, Akinwumi (2014) studied the soaked CBR of soil-slag mixtures with various slag content of 5, 8, and 10% by total weight. It reported that the soaked CBR values increased with increasing slag replacement. However, the soaked CBR values of the soil-slag mixtures even up to 10% slag replacement were lower than the soaked CBR value of the soil material. Similarly, soaked CBR test was carried out by Yadu et al. (2013) when various percentage of slag by 3, 6, 9, and 12% of the total weight were used to improve the mechanical properties of soil-slag blends. It demonstrated that the soaked CBR value of soil can be enhanced by slag replacement and the soaked CBR values of soil-slag mixtures increased with increasing slag replacement. However, its CBR values decreased when the slag replacement at 12%, which the authors reported that the bond between the soil and slag matrix were reduced due to the excess slag used. The experimental study on the utilization of steel slag stabilized high plastic subgrade soil by Aldeeky and Hattamleh (2017) also indicated that the CBR values of the soil-slag mixture increased with increasing slag replacement from 5 to 20% and then decreased at 25% of slag replacement. It is very interesting to note that the CBR values of the previous studies were fluctuated with the slag replacement, which contrast to this research that the CBR values increase with increasing CS replacement ratios from 0% to 50%. However, the swelling values were decreased with increasing all slag replacement ratios that is similar to the results in this research.

Based on an analysis of soaked CBR and swelling test results in this research, it is practical to relate the soaked CBR and swelling of blends at various compaction energies in term of CS replacement ratio as the improvement rate of CBR and swelling with CS replacement ratio is marginally dependent upon *E*. The predictive equations for soaked CBR and swelling in term of CS replacement ratio (**Figures 3.6** and **3.7**) are presented as follows:

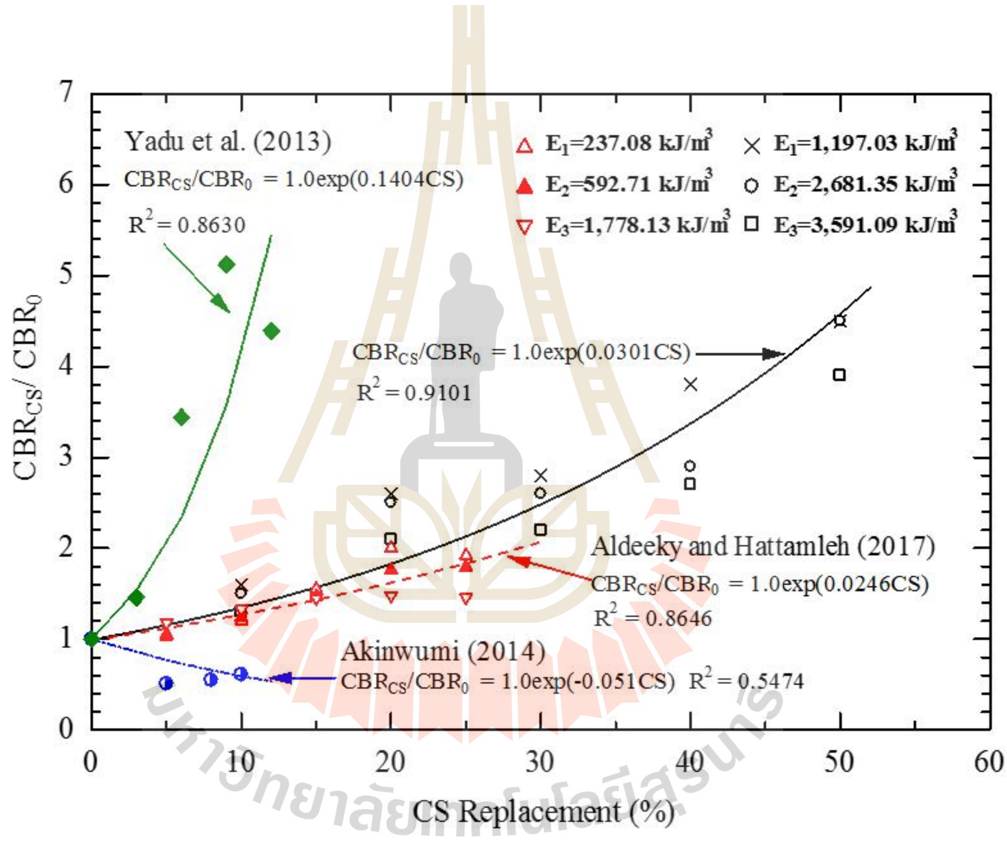
$$\frac{CBR_{CS}}{CBR_0} = 1.0\exp(0.030CS) \text{ for } 1197 \text{ kJ/m}^3 < E < 3591 \text{ kJ/m}^3 \quad (3.1)$$

$$\frac{S_{CS}}{S_0} = 1.0\exp(-0.016CS) \text{ for } 2681 \text{ kJ/m}^3 < E < 3591 \text{ kJ/m}^3 \quad (3.2)$$

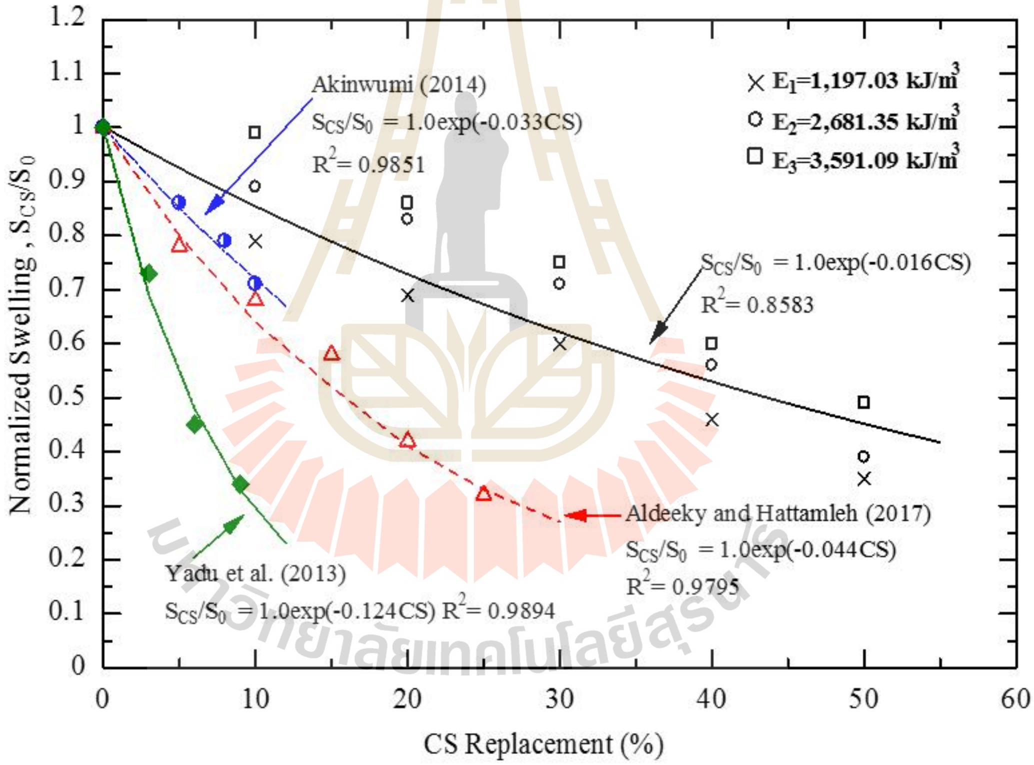
where $CBR_{CS}$ and $CBR_0$ are the soaked CBR at different CS replacement ratios (ranging from 0% to 50%) and soaked CBR at 0% CS replacement, respectively and $S_{CS}$ and $S_0$ are the swelling at different CS replacement ratios (ranging from 0% to 50%) and swelling at 0% CS replacement, respectively. These predictive equations are useful for predicting soaked CBR and swelling at different CS replacement ratios based on the values of LS (without CS replacement).

The CBR and swelling data from the previous similar studies have been adopted and applied in the proposed equations to verify its generalization and applicability. The results demonstrate that the applications of the proposed equations from various data are varied dependent upon the properties of the material studied, especially its size gradations. **Figure 3.6** indicates that the proposed equation generated from the CBR data in this research is in fair agreement with those data from Aldeeky and Hattamleh (2017) even though it is slightly higher when CS replacement is greater than 15%. This can be contributed to a reason that Aldeeky and Hattamle (2017) used a high plasticity clay (CH) with a slag that is classified as a well-graded sand (SW), which is comparable to the granular materials used in this study. With the same trend, however, the proposed equation overestimates the data from Akinwumi (2014). While, the significant different trends are observed between the data from Yadu et al. (2013) and the proposed equation in which it underestimates those data. The reason is that Akinwumi (2014) used the soil contained approximately 50% of fine with a high percentage of sand, which is classified as A-7-6(5) according to ASSTHO soil classification and a slag was 75% passing through 75 µm sieve opening. Whereas, an inorganic fine grained expansive soft soil in the classification of A-7-5(4) was used in Yadu et al. (2013) study with the fine slag particles. **Figure 3.7** shows that the normalize swelling, $S_{CS}/S_0$ for all swelling data decrease with increasing CS replacement. However, the proposed normalize swelling equation in this research overestimates for all data from those different studies.

Therefore, it can be concluded that the formulation of the predictive equations are on sound principle and applicable for the LS studied material and other similar soil materials that are within the bounds of the size gradations requirement



Yadu et al. (2013)
CBRCS/CBR0 = 1.0exp(0.1404CS)
R2 = 0.8630
E1=237.08 kJ/m3
E2=592.71 kJ/m3
E3=1,778.13 kJ/m3
E1=1,197.03 kJ/m3
E2=2,681.35 kJ/m3
E3=3,591.09 kJ/m3
CBRCS/CBR0 = 1.0exp(0.0301CS)
R2 = 0.9101
Aldeeky and Hattamleh (2017)
CBRCS/CBR0 = 1.0exp(0.0246CS)
R2 = 0.8646
Akinwumi (2014)
CBRCS/CBR0 = 1.0exp(-0.051CS) R2 = 0.5474
CBRCS/ CBR0
CS Replacement (%)



Normalized Swelling , $S_{CS}/S_0$
CS Replacement (%)
× $E_1$=1,197.03 kJ/m$^3$
○ $E_2$=2,681.35 kJ/m$^3$
□ $E_3$=3,591.09 kJ/m$^3$
Akinwumi (2014)
$S_{CS}/S_0$ = 1.0exp(-0.033CS)
$R^2$= 0.9851
$S_{CS}/S_0$ = 1.0exp(-0.016CS)
$R^2$= 0.8583
Aldeeky and Hattamleh (2017)
$S_{CS}/S_0$ = 1.0exp(-0.044CS)
$R^2$= 0.9795
Yadu et al. (2013)
$S_{CS}/S_0$ = 1.0exp(-0.124CS) $R^2$= 0.9894

The field construction can begin by roller-compacting the underlying subgrade in accordance with the specifications of the road authority. Marginal lateritic soil can next be mixed with CS at the construction site or ready mixed at an external plant. A mixture of lateritic soil and CS can then be compacted to attain a minimum of 95% modified Proctor density. Finally, the field density and CBR of the pavement samples can be measured for quality control purposes.

## 3.4 Conclusions

Marginal lateritic soil (LS) improvement by crushed slag (CS) replacement has been evaluated in this paper. The laboratory evaluation includes physical properties (particle size distribution, Atterberg limits and LA abrasion) and mechanical properties (CBR and swelling). The following conclusion can be drawn from this research study:

3.4.1. The CS improves both the physical and mechanical properties of marginal LS. Because the CS is a non-plastic and coarse-grained material, the liquid limit and plasticity index of LS reduce with increasing CS replacement contents. With low LA abrasion (of 17.3%) of CS, CS replacement enhances the durability against traffic load to the marginal LS.

3.4.2. Compaction breaks down the coarse grains of the LS and hence the increase in fine content. With higher abrasion resistance, the CS replacement improves the particle breakage due to compaction, resulting in lower fine content. This lower fine content of compacted blends with higher CS replacement ratios increases the soaked CBR and decreases swelling.

3.4.3. With the low water absorption of CS, both the water absorption and swelling of blends decrease with increased CS replacement. The rate of soaked CBR development and swelling reduction with CS replacement is essentially the same for all *E* values tested. Consequently, predictive equations for soaked CBR and swelling in term of CS replacement are proposed for various *E* values, which are useful for geotechnical and pavement practitioners. The soaked CBR and swelling of blends at various CS replacement ratios and *E* values can be predicted once the soaked CBR and swelling of LS (without CS) are known. The formulation of the proposed equations is based on soil mechanics principles and can be extended to other types of marginal soils.

3.4.4. The CS replacement improves the mechanical property of the original parent material and met the requirements for an engineering fill material, as defined by the Department of Highways, Thailand. In this research, the CS traditionally destined for landfill is found to be suitable as a replacement material to stabilize LS and found to be a sustainable engineering fill material. With a minimum 10% CS replacement content, the physical and mechanical properties of blends meet the requirements for engineering fill materials.



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# CHAPTER IV

# PHYSICAL, MECHANICAL AND DURABILITY IMPROVEMENT OF CEMENT STABILIZED MARGINAL LATERITIC SOIL BY CRUSHED SLAG/FLY ASH REPLACEMENT FOR PAVEMENT APPLICATIONS

## 4.1 Introduction

Lateritic soil (LS) is the most common construction material for roads in Thailand. Due to the lack of high quality LS, the modification of soils in-situ is an attractive, economical and environmental-friendly option to improve the mechanical properties of LS for high volume roads (Horpibulsuk et al., 2006, 2012 and 2013 and Du et al., 2013 and 2014).Marginal LS is often mixed with Portland cement for stabilized pavement base/subbase applications. The sustainable infrastructure development in Thailand and other developing countries has amplified the need to reuse waste materials as substitutes for natural resources, particularly in road construction projects. Recent studies in this field of sustainable pavement materials have merged the application of innovative ideas with geotechnical engineering techniques to target the reuse of recycled waste by-products in pavement applications (Arulrajah et al., 2014a and b and Ribeiro de Rezende et al., 2014). Donrak et al. (2016) has successfully utilized melamine debris blended with marginal LS to meet the engineering properties specified by the Department of Highways (DOH), Thailand for engineering fill materials. The usage of industrial wastes such as cement kiln dust, lime kiln dust and calcium carbide residue to stabilize marginal soils and demolition materials has also been studied in recent years (Kampala and Horpibulsuk, 2013; Kampala et al., 2013; Phetchuey et al., 2014; Arulrajah et al., 2017; Yoobanpot et al., 2017; and Mohammadinia et al., 2018).

Studies on recycled by-products as replacement material for marginal soils, in both the laboratory scale and in field studies have been reported to provide significant environmental impacts and cost-effectiveness (Donrak et al., 2018 and Sudla et al., 2018). These recycled materials include recycled glass for pavement and footpath bases (Disfani et al., 2014; Arulrajah et al., 2013, 2014a; 2014b and 2015), wastewater biosolids in road work embankments (Arulrajah et al., 2014), construction and demolition materials in combination with geotextiles in permeable pavements (Rahman et al., 2015), fine quarry wastes for pavement courses (Ribeiro de Rezende et al., 2014), overburnt distorted bricks as aggregates for pavement courses (Mazumder et al., 2006), sand reinforced with plastic wastes (Consoli et al., 2002), crushed brick as a supplementary material in bound pavements (Disfani et al., 2014), fly ash and slag based geopolymer stabilized recycled asphalt pavement as subbase/base materials (Hoy et al., 2016 and 2018). The utilization of recycled materials in road construction projects also has additional environmental benefits, such as reduction of construction and industrial wastes going to landfills.

According to the World Steel Association (WSA) report (2017), world crude steel production is approximately rising at the rate of 4.1% per year. The total steel production of 427 million tons was produced in the first three months of 2018, according to data collected by WSA from 64 countries. In Asia, crude steel production reached 294 million tons in 2018, which increased by 4.6% as compared to production in 2017. The European Union (EU) produced 43.1 million tons, up by 0.9% in 2017. North America produced 29.5 million tons, an increase of 1.9% compared to the production in 2017. These figures are significant when compared with the total world steel production in 2017, which was reported as 1,494 million tons (WSA, 2017). In Thailand, it is estimated that 1.5 million tons of steel are produced per annum (Sudla et al., 2018).

Crushed slag (CS) is a waste material generating from the steel manufacture process. Siam Steel Mill Services Co., Ltd., is the largest slag crushing company in Thailand, which reportedly releases 800,000 tons of CS annually. Presently, this CS is disposed by combustion to very high temperatures, which is a costly method and furthermore results in air-pollution. The sustainable usage of CS in civil engineering applications will lower the carbon footprint of future roads and also result in positive social and economic impacts for governments, industries and consumers.

The usage of CS for the improvement of marginal soil used for pavement applications is innovative and of interest to the industrial sectors and national road authorities as road construction typically requires a large volume of quality quarry material. CS has long been used in road construction as aggregates for the wearing coarse of asphalt concrete and as pavement base materials (Manso et al., 2005; Ahmedzade and Sengoz, 2009; Malasavage et al., 2012; Shahu et al., 2013; Tripathi et al., 2013; Yildirim et al., 2013; Du et al., 2015 and Maghool et al., 2016). CS was also used as a replacement material to improve the physical and mechanical properties of LS for subbase course based on the specification of Department of Highways, Thailand (Sudla et al., 2018). The mechanical properties of LS/CS blends can be further improved with cement, to enable these pavement material to carry higher loads. Fly ash (FA), which contains high pozzolanic materials with low specific gravity, can also be used together with CS to reduce the unit weight and enhance the cementation bonding.

The performance evaluation of the cement stabilized LS/CS/FA blends as a road material is still unknown and remains as a knowledge gap for the road construction industry. This paper investigates the strength development and durability against wetting and drying cycles of marginal LS blended with CS and FA, at various cement content and CS/FA ratios, as stabilized pavement sub-base and base materials. The outcome of this research is significant in terms of engineering, economical and environmental perspectives for producing a sustainable pavement material using recycled LS/CS/FA.

## 4.2 Materials And Methods

### 4.2.1 Materials

**Figure 4.1a** shows the studied marginal LS samples collected from a borrow pit in Muang district, Sakon-nakhon province, Thailand. The top soil of approximately 1.5 meter thickness was removed in order to obtain the LS sample. The LS contained approximately 21.7% fine-grained particles (passed No.200 sieve) and 78.3% coarse-grained particles (retained on No.200 sieve) in which 47.3% were gravel and 31% were sand. The specific gravity of coarse-grained particles was 2.67 and the liquid and plastic limits were 40.7% and 20.9%, respectively. The LS was classified as clayey gravel (GC) according to the Unified Soil Classification System (USCS) (ASTM-D2487-11, 2011). The grain size distribution curve for LS is shown in **Figure 4.2**. The maximum dry density (MDD) and optimum moisture content (OMC) of LS were 21.6 kN/m$^3$ and 7.25 %, respectively. The soaked California Bearing Ratio (CBR) value was 9.3%, while water absorption and swelling values were 4.19 and 6.40, respectively. The basic geotechnical properties are summarized in **Table 4.1**. The chemical compositions and mineral of LS, obtained by X-ray fluorescence (XRF) and X-ray diffraction (XRD) analyses, are presented in **Table 4.2** and **Figure 4.3a,** respectively. The XRD analyses indicated that the predominant mineral components in LS were muscovite and quartz, while the XRF results indicated that the main chemical compositions in LS were 65.08% $SiO_2$, 12.51% $Fe_2O_3$ and 12.41% $AlO_3$.

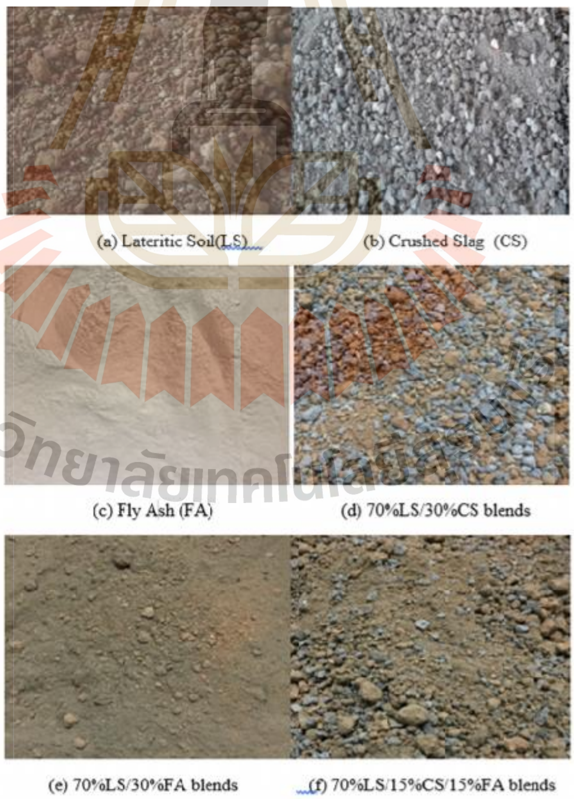



**Figure 4.1** Photos of (a) Lateritic Soil (LS), (b) Crushed Slag (CS), (c) Fly Ash (FA), (d) LS/CS blends, (e) LS/FA blends, (f) LS/CS/FA blends.

**Table 4.1** Geotechnical properties of LS, CS and LS/CS/FA blends

| Sample Description | CS | LS:CS:FA 70:30:0 | LS:CS:FA 70:15:15 | LS:CS:FA 70:0:30 | LS | Remark |
|---|---|---|---|---|---|---|
| Bulk specific gravity Coarse-grained | 3.35 | 2.77 | 2.76 | 2.68 | 2.67 | AASHTO T85-70 |
| Bulk specific gravity Fine-grained | 3.54 | 3.21 | 2.74 | 2.62 | 3.03 | AASHTO 84 |
| Apparent specific gravity Coarse-grained | 3.51 | 3.23 | 2.91 | 2.86 | 3.18 | AASHTO T85-70 |
| Apparent specific gravity Fine-grained | 4.26 | 3.73 | 3.04 | 2.69 | 3.47 | AASHTO 84 |
| Water absorption Coarse-grained (%) | 1.34 | 5.27 | 5.37 | 5.69 | 5.95 | AASHTO T85-70 |
| Water absorption Fine- grained (%) | 4.79 | 4.28 | 4.54 | 4.93 | 4.19 | AASHTO 84 |
| LA abrasion value (%) | 17.2 | 47.58 | 49.5 | 52.9 | 58.1 | ASTM C131 ,C535 |
| LL. (%) | - | 32.7 | 34.4 | 35.3 | 40.7 | AASHTO T90 |
| PL. (%) | - | 21.2 | 20.1 | 19.6 | 20.9 | AASHTO T90 |
| PI. (%) | - | 11.5 | 14.2 | 15.7 | 19.8 | |
| $D_{10}$ (mm) | 0.45 | - | - | - | - | |
| $D_{30}$ (mm) | 1.75 | 1.50 | 0.30 | - | 1.80 | |
| $D_{50}$ (mm) | 5.50 | 4.75 | 2.20 | 1.30 | 4.50 | |
| $D_{60}$ (mm) | 9.5 | 6.90 | 4.00 | 2.70 | 5.50 | |
| $C_u$ | 21.11 | - | - | - | - | |
| $C_C$ | 0.72 | - | - | - | - | |
| Gravel size content (%) | 53.3 | 49.2 | 41.9 | 35.2 | 47.3 | Retained #4 |
| Sand size content (%) | 43.4 | 31.6 | 29.1 | 28.8 | 31.1 | Passed#4-Retain#200 |
| Fines size content (%) | 3.3 | 19.2 | 29.0 | 36.0 | 21.7 | Passed#200 |
| Classification-USCS | GP | GC | GC | GC | GC | |

The CS samples used were obtained from the Siam Steel Mill Services Co., Ltd., located at Chonburi province, Thailand, were exposed to weather conditions for about 6 months. The CS particles are shown in **Figure 4.1b**. The physical properties of CS are also presented in **Table 4.1**. The bulk specific gravity of coarse-grained and fine-grained particles were 3.35 are 3.54, respectively. The CS was classified as non-plastic poorly graded gravel (GP) according to the Unified Soil Classification System (USCS). The grain size distribution curve of CS is shown in **Figure 4.2**. CS was composed of 3.3% fine-grained particles (passed No.200 sieve) and 96.7% coarse-grained particles (retained on No.200 sieve). The MDD and OMC of CS were 21.6 kN/$m^3$ and 7.25 %, respectively. The CS reactivity and mineralogy can be estimated from XRD and XRF analyses. **Table 4.2** and **Figure 4.3b** summarize the chemical compositions and mineral components of CS. The major components were 39.79% $Fe_2O_3$, 29.71% CaO, 13.15% $SiO_2$, and 4.28% $Al_2O_3$.

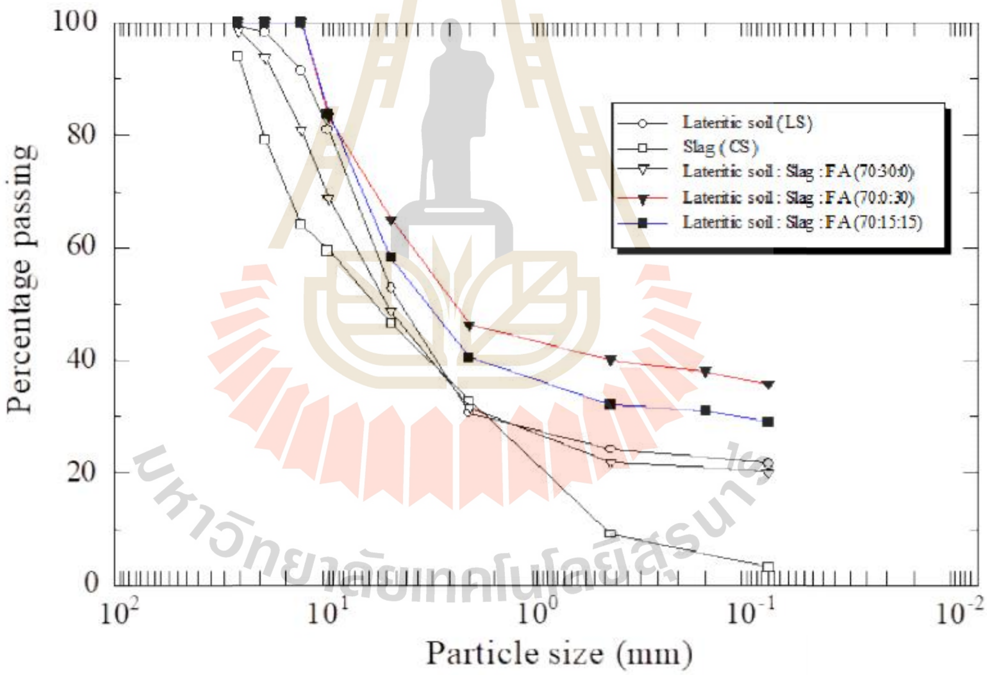



**Figure 4.2** Particle size distribution of LS, CS and LS CS blend at 30 CS replacement

**Table 4.2** Chemical composition of LS, CS, and FA.

| **Chemical formula** | **LS (%)** | **CS (%)** | **FA (%)** |
|---|---|---|---|
| $Na_2O$ | 0.70 | N.D | 0.62 |
| MgO | 0.84 | 1.75 | 2.53 |
| $Al_2O_3$ | 12.41 | 4.28 | 20.54 |
| $SiO_2$ | 65.08 | 13.15 | 38.14 |
| $P_2O_5$ | 0.86 | 0.69 | N.D |
| $SO_3$ | 0.07 | 0.31 | 0.49 |
| Cl | 0.40 | 0.03 | N.D |
| $K_2O$ | 4.21 | 0.05 | 1.56 |
| CaO | 1.01 | 29.71 | 12.38 |
| $TiO_2$ | 1.46 | 0.78 | N.D |
| $Cr_2O_3$ | 0.02 | 2.29 | N.D |
| MnO | 0.13 | 6.66 | N.D |
| $Fe_2O_3$ | 12.51 | 39.79 | 5.91 |
| CuO | 0.01 | 0.02 | N.D |
| LOI | 0.57 | 0.19 | 0.42 |



Fly ash (FA) was obtained from Mae Moh power plant, which is the largest lignite power plant of Electricity Generating Authority of Thailand (EGAT) in the northern region of Thailand. **Table 4.2** summarizes the chemical compositions of FA using XRF analysis. The major components were 38.14% $SiO_2$, 20.54% $Al_2O_3$, 5.91% $Fe_2O_3$, and 12.38% CaO. Therefore, it was classified as class C, high calcium fly ash (CaO > 10%) in accordance with (ASTM-C618, 2012). The FA particles are shown in **Figure 4.1c**, and its specific gravity was 2.50.

Type I Portland cement (C) was used as a stabilizer in this study. Two different cement dosages (3% and 5% by the dry weight of the LS/FA/CS blends) which are typically used for soil improvement projects in Thailand, were adopted to stabilize the marginal LS/CS/FA blends. Four different LS:CS:FA ratios studied were 100:0:0, 70:0:30, 70:15:15 and 70:0:30.

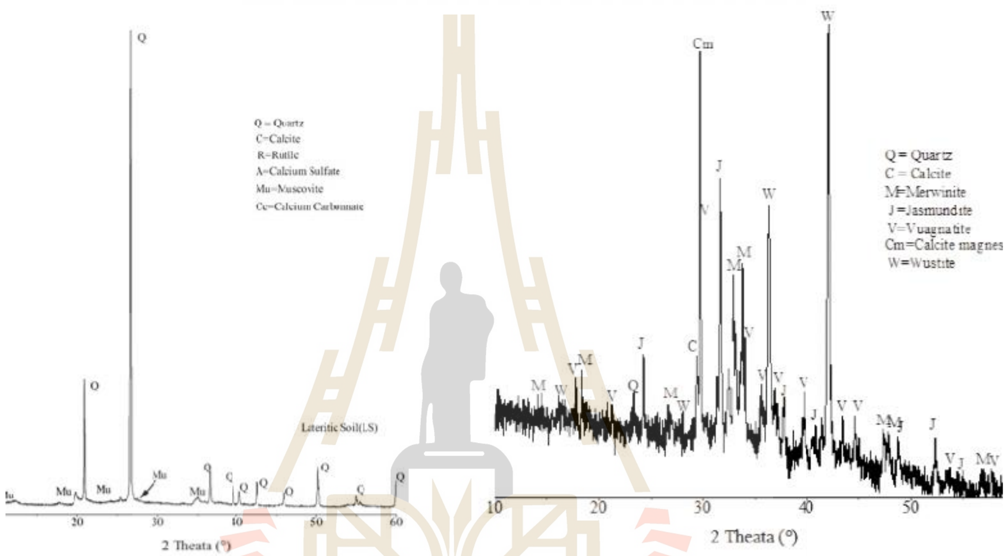



**Figure 4.3** XRD patterns of (a) LS and (b) CS.



**Table 4.1** presents the physical and mechanical properties of LS/CS/FA blends at LS:CS:FA ratios of 70:30:0, 70:15:15 and 70:0:30. The water absorption of coarse-grained LS (= 5.95%) was 4.4 times higher than that of CS (= 1.34%) while the water absorption of fine-grained CS (= 4.79%) was almost the same as that of fine-grained LS (= 4.19%). As such, the water absorption values of both coarse and fine grains for the LS/CS blends is higher than those for LS. The LA abrasion of the LS/CS/FA blends was improved by increasing the CS replacement ratio. The grain size distribution parameters including $D_{10}$, $D_{30}$, $D_{50}$, $D_{60}$, $C_u$, $C_c$, gravel, sand, and fine contents are also summarized in **Table 4.1**, which indicates that the coarse content of the LS/CS/FA blends increased, while the fine content decreased when increasing the CS replacement ratio. **Figure 4.2** shows the particle size distribution curves of the LS/CS/FA blends at various LS:CA:FA ratios.

### 4.2.2 Methods

The modified compaction tests on the LS/CS/FA blends were conducted according to the AASHTO T 180 to determine the MDD and OMC of the samples. Unconfined compression strength (UCS) tests were performed on the stabilized samples at OMC and MDD after 7, 14 and 28 days of curing and stored in a humidity-controlled room of constant temperature in according to ASTM D 1633 (ASTM 2000). The California bearing ratio (CBR) test method followed the AASHTO T 193 and the water absorption and swelling after 4 days of soaking were also measured.

The method of cyclic wetting and drying (w-d) test as per ASTM D 559-03 (ASTM 2003) was adopted in this research. The stabilized samples of 152 mm diameter and 116.43 mm height at the age of 28 days were used for w-d cycles test. One w-d cycle was constituted by submerging the samples in water for 5 hours and then drying them in the oven at a temperature of 70 °C for 48 hours and air-dried at room temperature for at least 3 hours. The 0, 3, 7 and 12 w–d cycles were considered in this study. After attaining the target w–d cycles, the samples were immersed in water for 2 hours at the constant temperature of 25 ± 2 °C prior to commencing the UCS test.

The growth of cementitious products in samples was examined using scanning electron microscopy (SEM). The SEM samples were frozen at -195°C by immersion in liquid nitrogen for 5 min and evacuated at a pressure of 0.5 Pa at - 40°C for 5 days (Horpibulsuk et al., 2010). All samples were coated with gold before SEM (JOEL JSM-6400) analysis.

## 4.3 Results And Discussion

### 4.3.1 Geotechnical properties and Compaction characteristics

Based on the Department of Highways specifications for stabilized base and subbase materials (**Table 4.3**), the gradation of the LS met the specified requirements. However, its LL and PI did not meet the specification requirements and hence must be improved before chemical stabilization. Due to the non-plastic characteristic of CS and FA, the CS and FA were blended with LS to improve index properties (LL and PI) before cement stabilization to meet the specified requirements of stabilized pavement materials. It is evident from **Table 4.3** that the LS:CS:FA ratios of 70:30:0 and 70:15:15 are suitable for both base and subbase applications while LS:CS:FA ratio of 70:0:30 is only suitable for subbase applications.

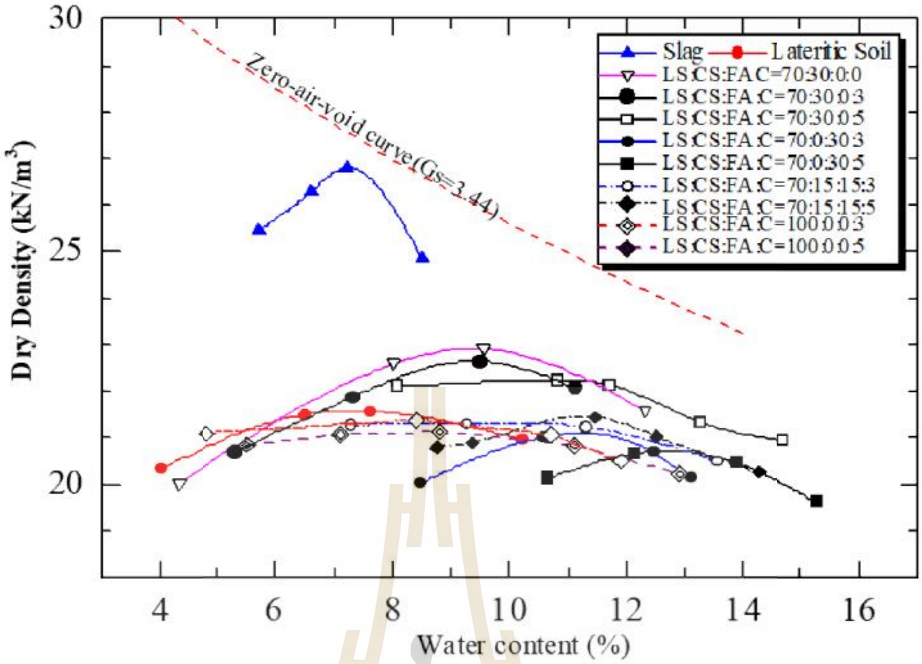



**Figure 4.4** A relationship between dry density and moisture content of the compacted samples.

The LA abrasion value reduces from 58.1% to 47.58%, LL reduces from 40.7% to 32.7% and PI reduces from 19.8% to 11.5% when LS is replaced by 30% CS content. When LS is replaced by 30% FA content, the LA abrasion value reduces from 58.1% to 52.9%, LL reduces from 40.7% to 35.4% and PI reduces from 19.8% to 15.7%. However, when LS is replaced by a combination of 15% CS and 15% FA content, the LA abrasion reduces from 58.1% to 49.50%, LL reduces from 40.7% to 34.4% and PI reduces from 19.8% to 14.2%

**Figure 4.4** shows the compaction test results of the stabilized LS/CS/FA blends at various CS and FA replacement ratios with 3% and 5% cement contents, compared with those of unstabilized samples. All compaction curves of LS/CS/FA blends exhibit bell-shaped compaction pattern, which indicates the typical of traditional geomaterials (Horpibulsuk et al., 2008, 2009 and 2013). The MDD of CS is relatively higher (26.9 kN/m$^3$) compared to that of LS (21.6 kN/m$^3$). For a particular CS replacement ratio, cement stabilization increases the OMC of the LS/CS/FA blends because of the higher water required for cement hydration. While the input of cement has minimal effect on the MDD of stabilized LS/CS blends similar to the finding by Horpibulsuk et al (2006).

**Table 4.3** Compared between typical specification from Department of Highways, Thailand and test result.

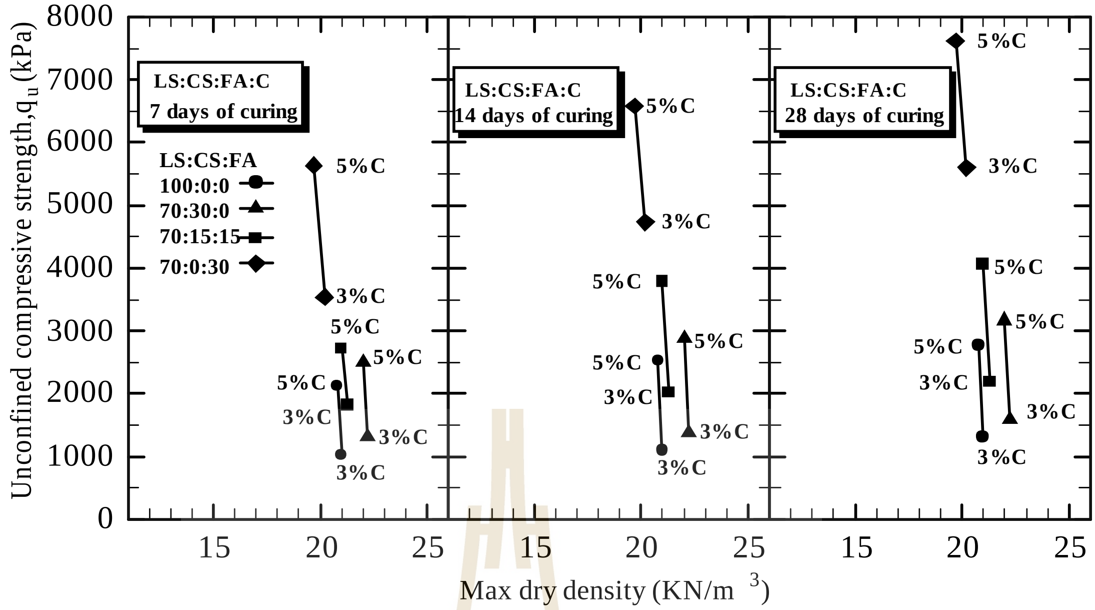
| Sample Description | Stabilized Sub-base (DH-S206/1989) | Stabilized Base (DH-S204/1990) | LS : CS : FA | | | | CS |
|---|---|---|---|---|---|---|---|
| | | | 100:0:0 | 70:30:0 | 70:15:15 | 70:0:30 | |
| Gradation | Max. size ≤ 50 mm. | Max. size ≤ 50 mm. | 25.4 | 25.4 | 25.4 | 25.4 | 25.4 |
| | NS. | Passed#10 ≤ 70% | 29.5 | 31.7 | 39.1 | 45.5 | 32.7 |
| | Passed#200 ≤ 40% | Passed#200 ≤ 25% | 21.7 | 19.2 | 29.0 | 36.0 | 3.3 |
| LA (%) | NS. | ≤ 60 | 58.1 | 47.58 | 49.5 | 52.9 | 17.2 |
| LL (%) | ≤ 40 | ≤ 40 | 40.7* | 32.7 | 34.4 | 35.4 | - |
| PI (%) | ≤ 20 | ≤ 15 | 19.8* | 11.5 | 14.2 | 15.7* | - |
| NS. = Not specified. | | | *Not meet specification | | | | |

For a particular C content, the OMC and MDD of the stabilized LS/CS blends reduces and increases, respectively with increasing CS replacement i.e., at C = 3%, OMC and MDD of the LS/CS blend are 11% and 21 kN/m3 for 0% CS replacement, while they are 10.8% and 22.23 kN/m3 for 30% CS replacement. On the other hand, the increase in FA replacement significantly increases OMC and reduces MDD of the stabilized LS/CS/FA blends; i.e., at C = 3%, OMC and MDD are 11.4%

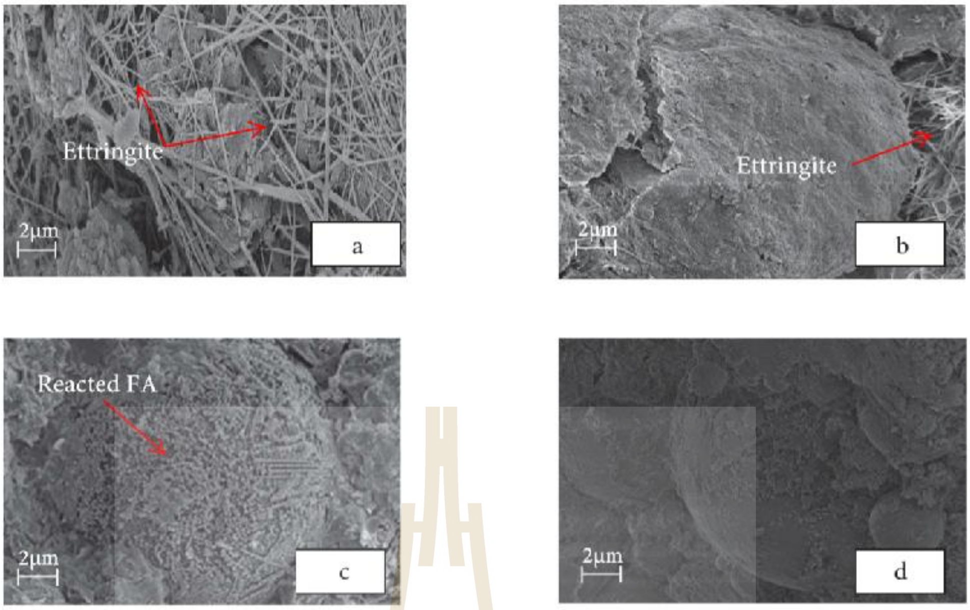
and 20.2 kN/m3 (for 30% FA replacement) and 11.0% and 21.3 kN/m3 (for 15% CS and 15% FA replacement). The LS/CS/FA blends have higher MDD than LS, as the specific gravity of CS (3.35) is higher than that of LS (2.67). The CS replacement reduces the plasticity of the mixtures due to the decrease in the amount of the silt-sized particles. The reduction in MDD of the LS/CS/FA blends with increasing FA replacement is due to the low unit weight of FA. This significant reduction in MDD can decrease the overburden on the foundation, which is an advantage over traditional stabilized pavement material.

### 4.3.2 UCS Characteristics

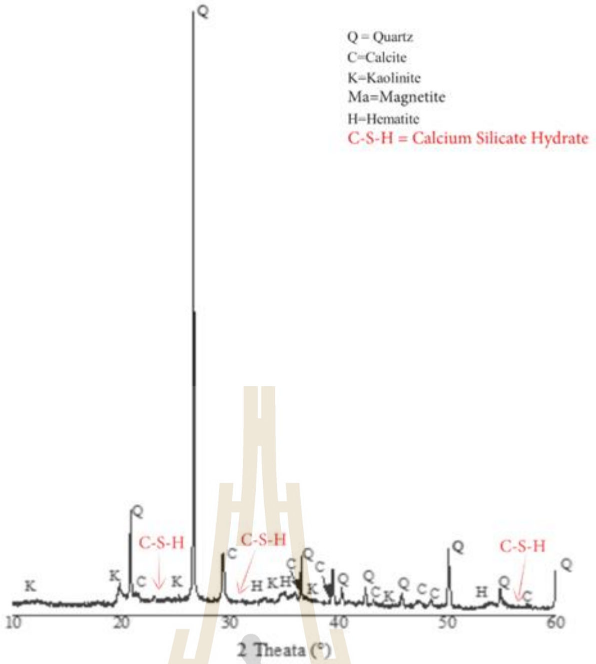
**Figure 4.5** shows the UCS of stabilized LS/CS/FA blends at various curing times (7, 14, and 28 days), cement contents (3% and 5%) and LS:CS:FA ratios (100:0:0, 70:30:0, 15:15 and 70:0:30). For a particular curing time, the UCS values of all samples increased with increasing cement content due to the cementation growth over time. At a particular cement content and curing time, the stabilized LS/CS/FA blends have higher UCS values than the unstabilized LS. The CS has a high LA abrasion value and hence can improve the mechanical properties of the LS/CS blends but causes higher maximum dry density. The high amount of calcium in FA can react with water and $Ca(OH)_2$ from cement hydration, resulting in higher UCS with lower maximum dry density. The LS:CS:FA = 70:0:30 provides the highest UCS and lowest maximum dry density for both 3% and 5% cement contents.



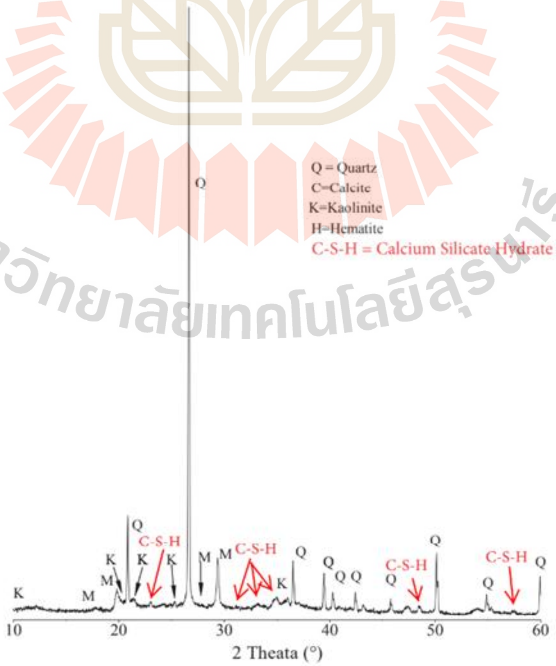
Unconfined compressive strength, $q_u$ (kPa)
Max dry density (KN/m $^3$)
LS:CS:FA:C
7 days of curing
LS:CS:FA:C
14 days of curing
LS:CS:FA:C
28 days of curing
LS:CS:FA
100:0:0
70:30:0
70:15:15
70:0:30
5%C
3%C



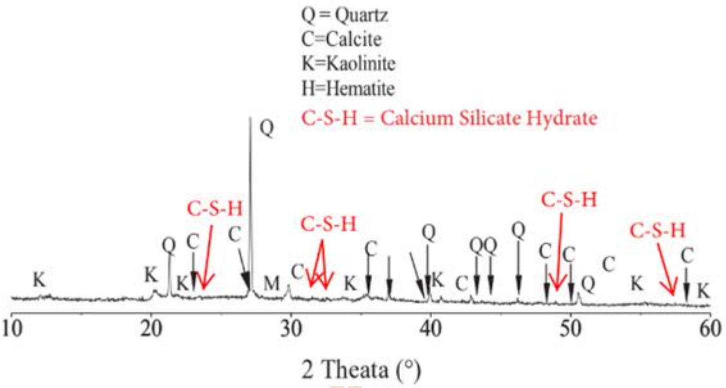
Ettringite
2μm
a
Ettringite
2μm
b
Reacted FA
2μm
c
2μm
d




a) LS:CS:FA = 70:30:0




(b) LS:CS:FA = 70:0:30




(c) LS:CS:FA = 70:15:15

**Figure 4.7** XRD patterns of 28 days cured samples for (a) LS:CS:FA = 70:30:0 with 5% C, (b) LS:CS:FA = 70:0:30 with 5% C, and (c) LS:CS:FA = 70:15:15 with 5% C.

### 4.3.4 Soaked CBR and Durability Against w-d Cycles

**Figure 8** shows the CBR and swelling results for both 3% and 5% C stabilized LS/CS/FA blends with various LS:CS:FA ratios. The soaked CBR value of cement stabilized LS (LS:CS:FA = 100:0:0) increases with increasing cement content (from C = 3% to C = 5%). The CS and/or FA replacements can dramatically increase the soaked CBR values of the C stabilized LS/CS/FA blends. However, the soaked CBR values of the stabilized blends at LS:CS:FA = 70:30:0 with 3% and 5% C contents are insignificantly different.

The FA replacement in the stabilized blends can also significantly enhance the soaked CBR. The soaked CBR values of both 3% and 5% C stabilized blends at LS:CS:FA = 70:0:30 and LS:CS:FA = 70:15:15 are higher than 200% and could not be measured as they are greater than the load capacity of the proving ring.

This result implies that CS and/or FA replacements can improve the durability of the cement stabilized LS, which is particularly advantageous for earth-work applications which requires the presence of durable material against soaking condition. The swelling behavior of the cement stabilized LS:CS:FA blends also illustrated in **Figure 4.8**. The unstabilized LS material indicates the highest swelling value, about 6.5%. The swelling value of the unstabilized LS is reduced to approximately 4% when CS and/or FA replacements are blended with LS, even without cement content.

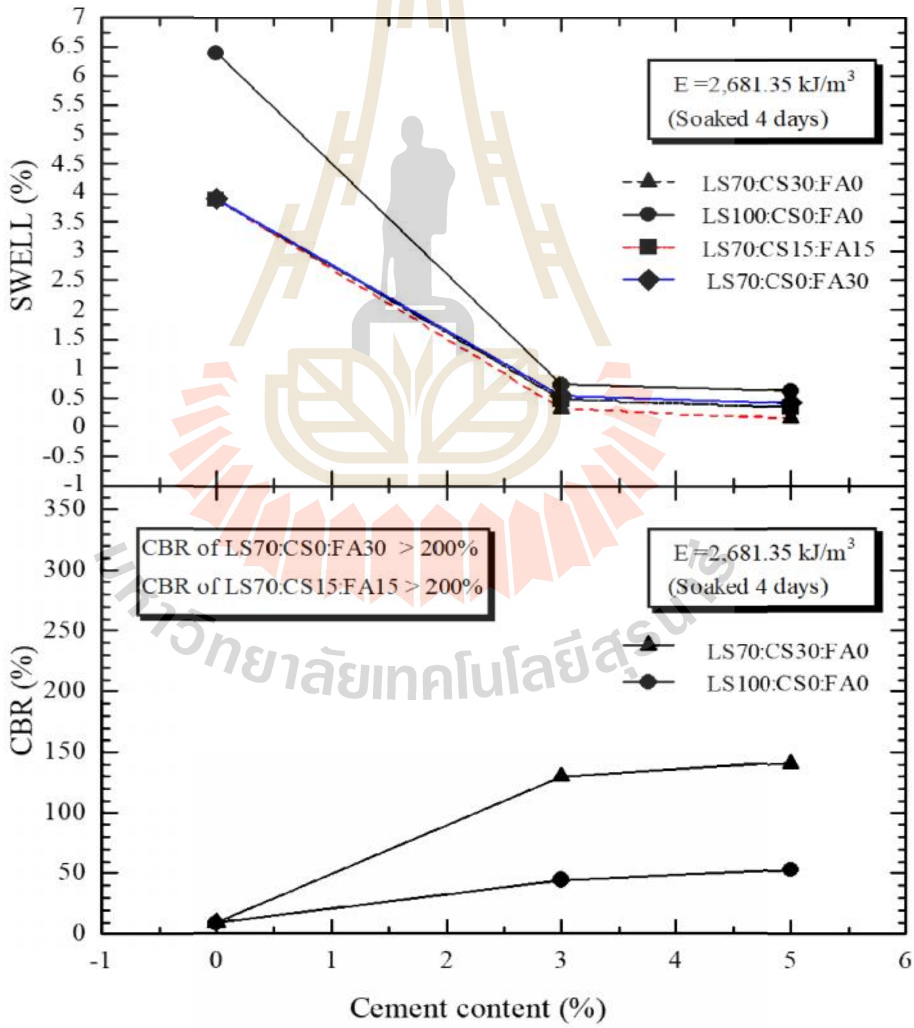
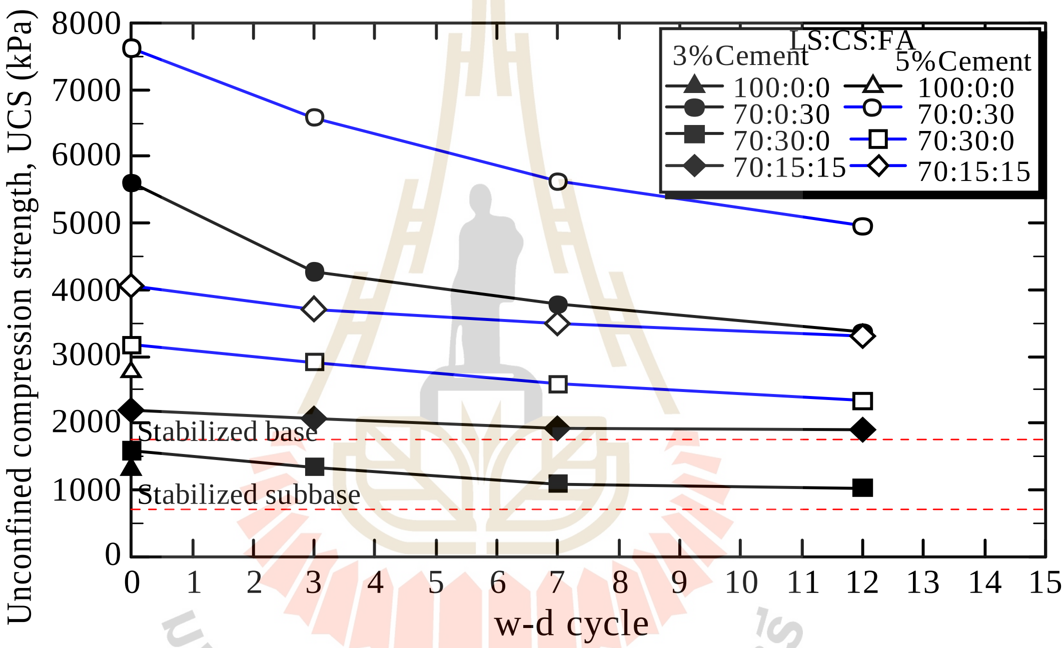
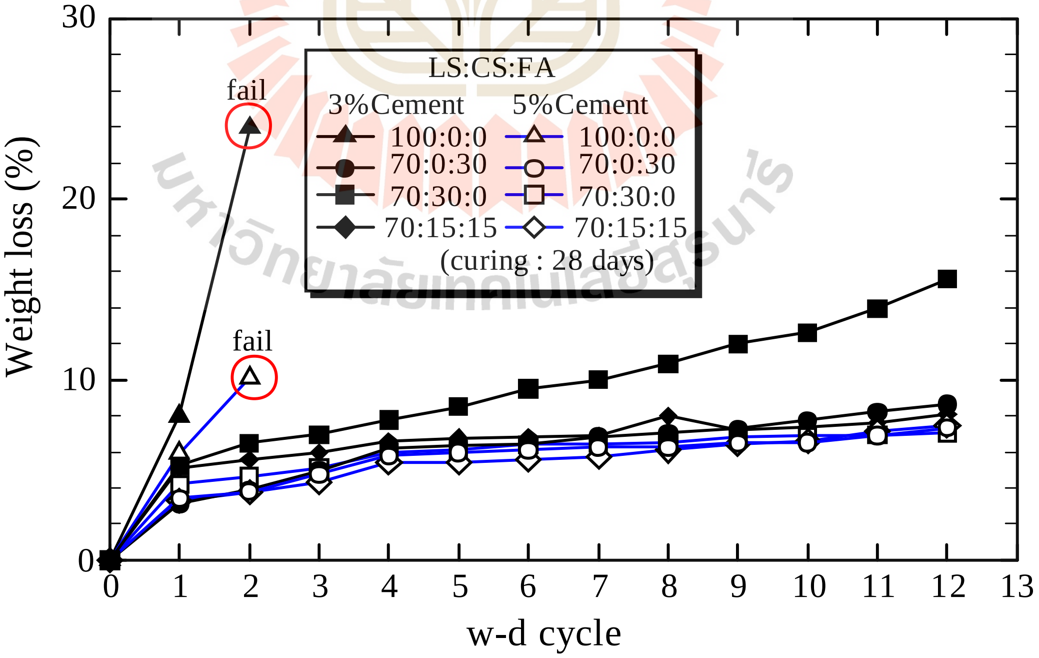



**Figure 4.8** A relationship between Swelling/CBR and cement contents for LS/CS/FA blends.


Unconfined compression strength, UCS (kPa)
w-d cycle
LS:CS:FA
3%Cement
5%Cement
100:0:0
70:0:30
70:30:0
70:15:15
Stabilized base
Stabilized subbase
0
1000
2000
3000
4000
5000
6000
7000
8000
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15


30
20
10
0
Weight loss (%)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
w-d cycle
fail
fail
LS:CS:FA
3%Cement
5%Cement
100:0:0
70:0:30
70:30:0
70:15:15
100:0:0
70:0:30
70:30:0
70:15:15
(curing : 28 days)

The physical surface examination can be satisfactorily used to explain the sample deterioration. The effect of cyclic w–d cycles on the external surface of 3% and 5% C LS/CS/FA blends at LS:CS:FA = 70:30:0, 70:15:15 and 70:0:30 is presented in **Figures 4.11** and 4.**12** at *N* = 0, 3, 7 and 12. Due to the water loss during the w-d cycles process, the primary cracks grow on the sample's surface and the macro-cracks develop with increasing *N*, which lead to strength loss of the stabilized materials (Hoy et al., 2017). The macro-cracks and surface deterioration are observed on the 3% C stabilized LS:CS:FA = 70:30:0 samples at *N* = 7 and 12 as shown in **Figure 4.11a**. The stabilized mixture at LS:CS:FA = 70:30:0 with 3% C therefore has the lowest UCS values after w-d process. The surface deterioration on the 3% C sample at LS:CS:FA = 70:0:30 is observed at the third w-d cycle (**Figure 4.11b**), hence the remarkable reduction in UCS value is noted. However, with further increasing *N*, its physical surface was insignificantly changed. While, the surface cracks of the 3% C samples at LS:CS:FA = 70:15:15 are more or less the same for *N* = 3, 7, and 12 (**Figure 4.11c**). This implies that the samples are in a stable state, which results in less UCS reduction. Comparing **Figure 4.12** with **4.11**, it visibly demonstrates that the surface crack on the 5% C samples at all LS/CS/FA blends are less than that 3% C samples. This indicates that the utilized cement content up to 5% in the stabilized mixtures can enhance the durability of the blends.

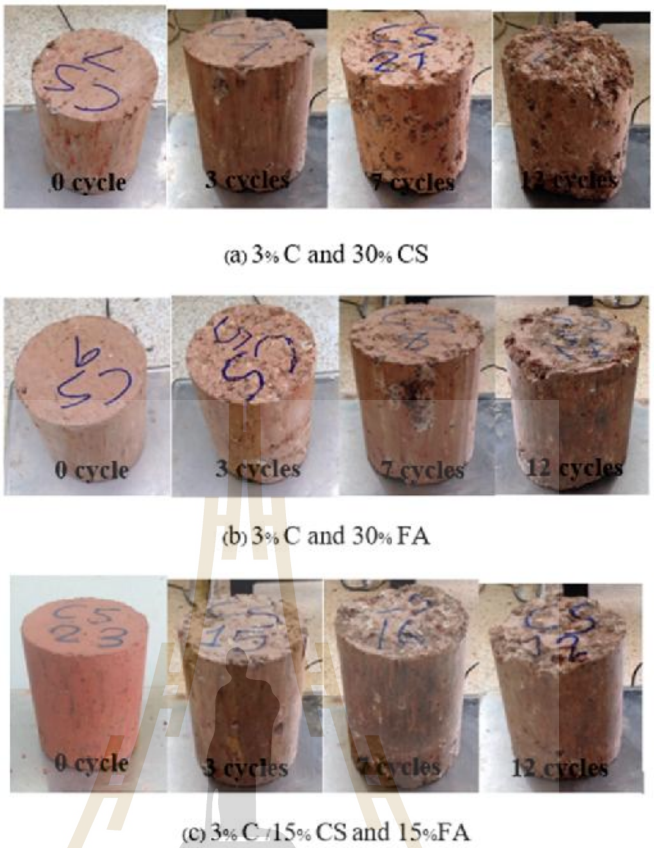



**Figure 4.11** Photos of (a) 3% C and 30% CS, (b) 3% C and 30% FA, (c) 3% C and 15% CS and 15% FA after 0, 3, 7 and 12 w-d cycles.


(a) 5% C and 30% CS


(b) 5% C and 30% FA


(c) 5% C and 15% CS and 15%FA

stabilized subbase by up to 12 cycles while LS:CS:FA = 70:0:30 and 70:15:15 can prolong the service of stabilized base by up to 12 cycles. The 5% C stabilized LS/CS/FA blends with all LS:CS:FA ratios (70:30:0, 70:15:15 and 70:0:30) can resist the w-d cycles up to 12 cycles but it is not economic when compared with the 3% C stabilized LS/CS/FA blends.

### 4.3.5 Environmental Impact Assessment

To be used as a sustainable material, even due to rainfall or stormwater events, the cement stabilized LS/CS/FA blends must not pose any risk to the groundwater tables or water streams beyond. Therefore, in order to use the cement stabilized LS/CS/FA blends in road construction, the environmental risk assessment needs to be ascertained. **Table 4.4** shows the measured leachate heavy metal concentrations for 5% C stabilized LS/CS/FA blend and 5% C stabilized LS blend using acetic leachate extraction and is compared with those of drinking water by the U.S. Environmental Protection Agency (EPA., 2009a and 2009b). Wartman et al. (2004) reported that a material is designated as a hazardous waste according to U.S EPA if any detected metal is present in concentrations greater than 100 times the drinking water standards. Based on this criterion, **Table 4.4** indicates that all metal contaminants are within allowable limits.

**Table 4.4** Leachate analysis data for CS and 5% C stabilized LS ,LS /CS/FA blend.

| Parameter | Samples of acid leachate extraction (mg/L) | | | | | Drinking water regulations (EPA, 2009a) (mg/L) |
|---|---|---|---|---|---|---|
| | CS | 5% C stabilized LS | 5% C stabilized 70/30/0 (LS/CS/FA) | 5% C stabilized 70/15/15 (LS/CS/FA) | 5% C stabilized 70/0/30 (LS/CS/FA) | |
| pH | 5.48 | 4.37 | 5.24 | 4.89 | 4.53 | 6.5 - 8.5 |
| Arsenic | BDL | BDL | BDL | BDL | BDL | 0.01 |
| Cadmium | BDL | BDL | BDL | BDL | BDL | 0.005 |
| Chromium | BDL | 0.058 | 0.032 | 0.045 | 0.097 | 0.1 |
| Copper | BDL | BDL | BDL | BDL | BDL | 1.0 |
| Lead | BDL | BDL | BDL | BDL | BDL | 0.015 |
| Mercury | BDL | BDL | BDL | BDL | BDL | 0.002 |
| Nickel | BDL | 0.042 | 0.037 | 0.038 | 0.041 | - |
| Zinc | 0.533 | 0.067 | 0.108 | 0.074 | BDL | 5.0 |
| BDL = Below Detection Limit(<0.01 mg/L) | | | | | | |

The results indicate that 5% C stabilized LS/CS/FA blend is mechanically and economically viable for use in pavement base/subbase applications. Besides good mechanical properties, the 5% C stabilized LS/CS/FA blend provides a positive environmental impact as environmental test results show no significant risk to the groundwater or stream water line.

## 4.4 Conclusions

This article investigated the influence of CS and FA replacement on the improvement of physical, mechanical and durability properties of cement stabilized marginal LS to ascertain its serviceability as pavement subbase and base courses. LS was found to be unsuitable for subbase/base material applications, due to its inferior index properties. The index properties of LS was improved by CS and/or FA replacements and met the specification for cement stabilized subbase/base specified by the Department of Highways, Thailand. Also, the CS and FA replacement reduced the fine aggregates and improved particle strength, hence significantly enhanced the UCS of the C stabilized LS/CS/FA blends at the same C contents.

Even though the 3% and 5% C stabilized LS had very high UCS of more than 1200 kPa, they failed after 2nd w-d cycle, showing the low durability. In addition to the physical and UCS properties, the CS and FA replacement could increase the soaked CBR, durability and also reduce the swelling of the cement stabilized LS/CS/FA blends. The high calcium FA fill the pores and reacted with $Ca(OH)_2$ from cement hydration while the CS had high potential on minimizing the swelling, which control the durability of the stabilized material. Therefore, the combination of CS and FA replacement in the mixtures provided a dense matrix of stabilized materials. The sample with a higher FA replacement had higher UCS at various *N* due to high cementitious products, yet the samples with higher CS replacement had lower rate of UCS reduction over *N*. The CS and/or FA replacement improved the durability of cement stabilized LS, which is particularly advantageous for some applications which requires durable material against soaking condition. Based on the specification of the Department of Highways, Thailand, the 3% C samples can be used as subbase material when blended with 30% CS replacement and as base material when blended with CS and FA at LS:CS:FA = 70:0:30 and 70:15:15. The 30% CS replacement can prolong the service life of stabilized subbase up to 12 cycles while LS:CS:FA = 70:0:30 and 70:15:15 can prolong the service of stabilized base up to 12 cycles.

The leachability of the heavy metals of the cement stabilized LS/CS/FA blends was measured and compared with international standards. The leachate results indicated that the cement stabilized LS/CS/FA blends can be safely used in sustainable pavement applications, as the leachate heavy metal concentrations were within the acceptable range.

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# CHAPTER V

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Summary And Conclusions

This thesis consists of three main objectives. The first objective is to investigate a possibility of using crushed slag (CS) as a replacement material to improve mechanical properties of marginal lateritic soil (LS). The second objective is to evaluate physical, mechanical and durability properties of cement stabilized LS/CS/FA blends. The third objective is to investigate the environmental assessment of LS/CS/FA blends with cement stabilization to ascertain them as green pavement materials. The conclusions can be drawn as follows:

### 5.1.1 CS as replacement material to improve mechanical properties of LS

Firstly, a completed set of geotechnical laboratory program was conducted to attest the possibility of using CS replacement to improve the basic engineering property of LS in order to meet the requirement for engineering fill material according to national local authority. With a minimum 10% CS replacement, the physical and mechanical properties of LS/CS blends meet the requirement. Because the CS is a non-plastic and coarse-grained material, the liquid limit and plasticity index of LS reduce with increasing CS replacement contents. With the low water absorption of CS, both the water absorption and swelling of LS/CS blends decrease with increased CS replacement. Compaction breaks down the coarse grains of the LS, which results in an increase in fines content. However, with higher abrasion resistance, the CS replacement improves the particle breakage due to the compaction, resulting in a lower fines content. This lower fines content of compacted blends with higher CS replacement contents increases the soaked CBR and decreases swelling.

### 5.1.2 Durability of cement stabilized of LS/CS/FA blends

LS, is typically blended with CS (non-plastic materials) to improve its gradation and swelling characteristics and subsequently stabilized with Portland cement (C) to form pavement subbase and base materials. Based on the specification of the Department of Highways, Thailand, the 3% C samples can be used as subbase material when blended with 30% CS replacement and as base material when blended with CS and FA at LS:CS:FA = 70:0:30 and 70:15:15. The 30% CS replacement can prolong the service life of stabilized subbase up to 12 cycles while LS:CS:FA = 70:0:30 and 70:15:15 can prolong the service of stabilized base up to 12 cycles. The CS and/or FA replacement improve the durability of cement stabilized LS, which is particularly advantageous for some application srequiring durable material against soaking condition. The high calcium FA fills the pores and reacts with $Ca(OH)_2$ to form cement hydration while the CS has high potential on minimizing the swelling, which controls the durability of the stabilized material.

### 5.1.3 Environmental assessment of cement stabilized LS/CS/FA

To be used as a sustainable pavement material, even due to rainfall or stormwater events, the cement stabilized LS/CS/FA blends must not pose any risk to the groundwater tables or water streams beyond. Therefore, the environmental risk assessment needs to be ascertained. Toxicity Characteristic Leaching Procedure (TCLP) test was conducted to examine the leached heavy metals from the cement stabilized LS/CS/FA blends. TCLP results indicat that the 5% C stabilized LS/CS/FA blends can be safely used in sustainable pavement applications, as the material poses no significant environmental and leaching hazards into the soil, surface and ground water sources. This study indicates that CS can be considered as an environmentally friendly pavement material,

## 5.2 Recommendations for future work

- Study a field performance of cement stabilized LS/CS/FA blends.
- Develop a design method for road pavement using cement stabilized LS/CS/FA blends.

# APPENDIX A

# LIST OF PUBLICATIONS

# List of Publications

Sudla, P., and Horpibulsuk, S., **A Study on Physical and Geotechnical Properties of Crushed Slag Improved Marginal Lateritic Soil for Pavement Applications.** Proceeding of the International Conference on Advances in Civil Engineering for Sustainable Development (ACESD 2014), 27-29 August 2014, Nakhon Ratchasima.

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จีรพรรณ ดลรักษ์, สำเร็จ สารมาคม, พุฒิพงศ์ สุดหล้า, สุขสันติ์ หอพิบูลสุข ( 2558) **คุณสมบัติของดินลูกรังด้อยคุณภาพผสมเศษวัสดุจากอุตสาหกรรมผลิตภาชนะจากเมลามีนเพื่อใช้ในงานโครงสร้างทาง.** การประชุมวิชาการวิศวกรรมโยธาแห่งชาติครั้งที่ 20, ชลบุรี.8-10 กรกฎาคม 2558

Available online at www.sciencedirect.com

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Soils and Foundations 58 (2018) 786–795

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# Marginal lateritic soil/crushed slag blends as an engineering fill material

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Received 12 May 2017; received in revised form 28 February 2018; accepted 8 March 2018

**Abstract**

Lateritic soil (LS) with suitable mechanical properties is commonly used as the subbase and as engineering fill material in roads. However, LS is becoming increasingly scarce as a source for road projects. The usage of marginal LS as a pavement subbase and engineering fill material leads to some challenging issues that this research seeks to address. This paper evaluates the possibility of using crushed slag (CS), a waste by-product, as a replacement material to stabilize marginal LS for engineering fill applications. An investigation was undertaken on the physical and mechanical properties of the LS/CS blends at various CS replacement contents. The laboratory evaluation program included particle size distribution, specific gravity, water absorption, Los Angeles (LA) abrasion, Atterberg limit, California Bearing Ratio (CBR) and swelling tests. CS replacement was found to reduce the fine content and increase the abrasion resistance of the marginal LS, resulting in a reduction in liquid limit, plasticity index, LA abrasion and particle breakage. With increases in the CS replacement content, a marked improvement in the physical properties of the blends was found, including increased soaked CBR and reduced swelling. Normalized $CBR_{CS}/CBR_0$ and $S_{CS}/S_0$ and CS replacement relationships were developed in this research. $CBR_{CS}$ and $S_{CS}$ are the CBR and swelling values at various CS replacement contents, respectively and $CBR_0$ and $S_0$ are the $CBR_0$ and swelling values at a 0% CS replacement content, respectively. The results are expected to be of interest to both geotechnical and pavement practitioners. The physical and mechanical properties of the blends with a minimum of 10% CS replacement content were found to meet the national local road authority requirements for engineering fill material.



*Keywords:* Crushed slag; Marginal lateritic soil; Fill; Waste; Recycled material

## 1. Introduction

Highway pavement generally consists of base, subbase and engineering fill layers, which are typically constructed from suitable materials such as crushed rock and lateritic

Peer review under responsibility of The Japanese Geotechnical Society.

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https://doi.org/10.1016/j.sandf.2018.03.007

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soil (LS). Due to high rainfall, temperature and humidity with alternative wet and dry periods, nearly 60% of the soils in Thailand are LS with colors ranging from red to yellowish red. LS mostly originates from igneous rocks and comprises well drained residues with the presence of excessive iron and aluminum oxides. LS is found in dry flat plains throughout Thailand. This LS with suitable mechanical properties is commonly used as a subbase and engineering fill material in roads. LS consists of coarse- and fine-grained particles, and it is becoming increasingly scarce as a source for road projects. Because LS with a high percentage of fine-grained particles has some unfavorable properties which result in shrinkage during dry seasons and swelling during wet seasons, which are exacerbated due to its water sensitivity and uneven distribution, it is often only considered appropriate for use as subgrade materials (Phummiphan et al., 2015, 2016; and Suebsuk et al., 2017). The usage of marginal LS as a pavement subbase and engineering fill material, therefore, leads to some challenging issues that this research seeks to address. A practical improvement method for marginal LS is to blend it with suitable materials, followed by simple and cost-effective compaction to enhance interlocking between coarse-grained and fine-grained particles (Horpibulsuk et al., 2008, 2009; Bo et al., 2014 and Donrak et al., 2016). Compacting in-situ soil mixed with alternative virgin aggregates is a common and economical option to modify LS to achieve the adequate mechanical properties for roadway construction. (Chinkulkijniwat and Horpibulsuk, 2012; Horpibulsuk et al., 2006, 2013b). This replacement method is considered a more cost-effective and environmental-friendly technique if the recycled and/or waste materials are used as an alternative material to substitute virgin aggregates. Hence, this technique can reduce the cost of the roadway construction and give the positive environment impacts.

Waste is generally considered to have no lasting value. A large quantity of municipality solid waste is generated by industrial, human and commercial activities. Recycling is a method of converting various wastes into useful material that can be reused. Without a proper recycling process, these wastes are undesirable materials that are disposed to landfills, which can result in numerouss environmental problems. For instance, some waste contains metal or toxic compounds that can contaminate the soil, surface and ground water.

In recent decades, innovative research works has been undertaken to convert waste into a source of material that can substitute virgin aggregates in pavement applications. This sustainability approach has been endorsed by government, commercial, industrial and education sectors. Steel slag has been used to improve soils with poor engineering properties and reported as a low-cost soil modification technique (Akinwumi, 2014). The physical and mechanical properties of the soil/slag blend were characterized by geotechnical laboratory experimental program, including sieve analysis, consistency limits, specific gravity, compaction, California bearing ratio (CBR), unconfined compressive strength (UCS) test. Yadu et al. (2013) investigated the physical and strength properties of a soft soil and slag mixture and reported that the utilization of an optimum amount of slag can reduce the free swelling index and lead to improve the soaked CBR and UCS.

The scientific and practical methodologies and outcomes from previous research have been reviewed and summarized in this paper in order to make a new illuminating study on cleaner production as well as to assure that waste materials can be mixed with soil as an intuitive practitioner interface technique in pavement applications.

Crushed steel slag (CS) is a by-product produced during the conversion of iron ore from scrap iron to steel. Steel slags are generated during both steelmaking and refining operations. There are two separate primary steelmaking processes that produce steel slag as a by-product; (i) the basic oxygen furnace (BOF) process and (ii) the electric arc furnace (EAF) process (Lizarazo-Marriaga et al., 2011; Maghool et al., 2017). The mineralogical composition of steel slag depends on its chemical components. The common minerals in steel slag are olivine, merwinite, di-calcium silicate, tricalcium silicate, tetra-calcium aluminoferrite, di-calcium ferrite, solid compound of CaO–FeO–MnO–MgO, and free lime (Sentien et al., 2009).

In Thailand, steel slag is predominantly produced using the electric arc furnace (EAF) process. The accumulation of CS waste material is approximately 1.5 million tons per annum from total steel production in Thailand. CS has been used in road construction as aggregates of wearing coarse asphalt concrete and as base materials (Manso et al., 2005; Ahmedzade and Sengoz, 2009; Malasavage et al., 2012; Shahu et al., 2013; Tripathi et al., 2013; Du et al., 2015 and Maghool et al., 2016). CS can also be used for soil improvement, such as the usage of basic oxygen steel slag fines for soil and dredged material stabilization (Poh et al., 2006), as well as the usage of ladle furnace slag as an embankment material (Montenegro et al., 2013). The evaluation of CS as a replacement material to stabilize marginal soil and the assessment of mechanical properties such as California bearing ratio and swelling have yet to be satisfactorily understood.

This research aims to investigate the physical and mechanical properties of marginal LS/CS blends at various replacement contents to evaluate them as an engineering fill material. Since CS has a higher unit weight than LS, a higher CS replacement results in the higher bearing stress on the subgrade and foundation. To minimize the unit weight of the stabilized material, the CS replacement should be within 50% of the marginal soil. Furthermore, because construction sites are typically far away from CS sources, the high haulage costs mean that a greater CS replacement content is not an economical option. This research will enable CS, a waste material traditionally destined for landfill, to be used as a non-plastic replacement material for marginal LS improvement. This research is significant in terms of engineering, economical and environmental perspectives. The usage of CS in marginal LS improvement for pavement applications is innovative and of interest to the industrial sectors and national road authorities, particularly as road construction requires a large volume of quality materials.

## 2. Materials and methods

Marginal LS was collected from a borrow pit in Muang district, Sakonnakhon province, Thailand (Fig. 1a) at approximately 1.5 m depth from the ground surface. The LS was composed of 21.7% fine-grained particles, and 78.3% coarse-grained particles in which 47.3% is gravel and 31.0% is sand. The specific gravity of coarse-grained particles is 2.67 and liquid and plastic limits are 40.7% and 20.9%, respectively. According to the Unified Soil Classification System (USCS), this LS is classified as clayey gravel (GC). The grain size distribution curve is shown in Fig. 2 and physical properties are summarized in Table 1. By comparing with the specification for sub-base and engineering fill materials (DS-205/2532) from the Department of Highways, this LS does not meet the standards and requires an improvement in its mechanical properties to enable it to be used as engineering fill material.

Crushed slag (CS) used in this research was obtained from Siam Steel Mill Services Co., Ltd., Chonburi province, Thailand. CS particles are shown in Fig. 1b. The physical properties of CS are also presented in Table 1. The bulk specific gravity of coarse-grained and fine-grained particles are 3.35 are 3.54, respectively. According to USCS, CS is classified as non-plastic poorly graded gravel (GP). The grain size distribution curve of CS is shown in Fig. 2. It was found that the CS is composed of 3.3% fine-grained particles and 96.7% coarse-grained particles.

The LS:CS contents studied were in proportions of 50:50, 60:40, 70:30, 80:20 and 90:10 based on weight. Fig. 1c shows the photo of the LS/CS blend at 50% CS replacement. The laboratory evaluation program on marginal LS/CS blends includes the following: (i) specific gravity, (ii) water absorption, (iii) Atterberg limit, (iv) modified Proctor compaction, (v) Los Angeles (LA) abrasion, and (vi) California Bearing Ratio (CBR) tests. All tests were undertaken following relevant American Association of State Highway and Transportation Officials (AASHTO) and American Society for Testing and Materials (ASTM).

Specific gravity and water absorption tests of coarse-grained particles were performed in accordance with AASHTO T 85-70. For fine-grained particles, the specific gravity and water absorption tests were performed in accordance with AASHTO T 84. Atterberg limit tests were performed in accordance with AASHTO T 90. Particle size distribution analysis tests were performed in accordance with AASHTO T 27-70. A particle size distribution analysis and Atterberg tests were conducted on samples both before and after modified compaction tests to investigate the particle breakage due to compaction.

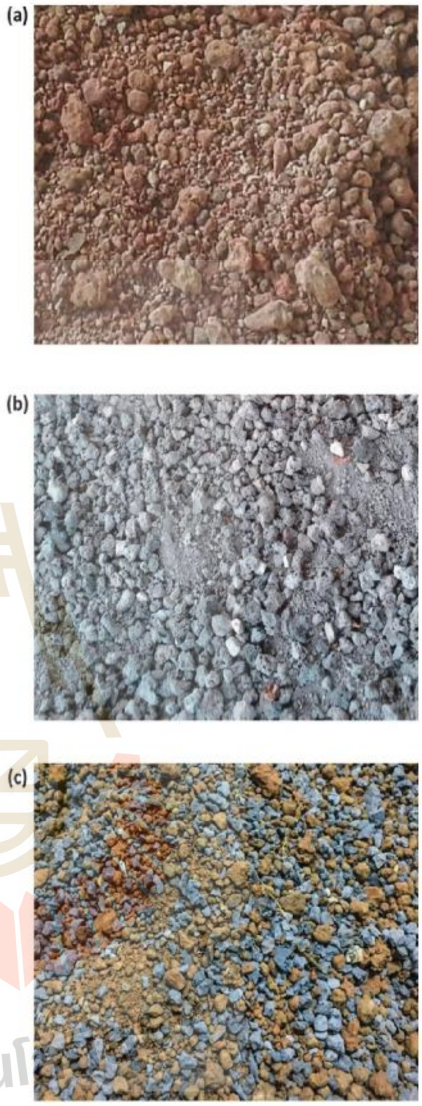


Fig. 1. (a) Lateritic Soil (CS) (b) Crushed slag and (c) Lateritic soil/CS blends.

Based on the specification for pavement material construction by the Department of Highways and Department of Rural Roads of Thailand, base, subbase and engineering fill materials must be compacted under modified compactive energy while the subgrade must be compacted under standard compactive energy. Modified compaction tests were then conducted on the LS/CS blends by following the AASHTO T 180 to determine the maximum dry density (MDD) and optimum moisture content (OMC) of

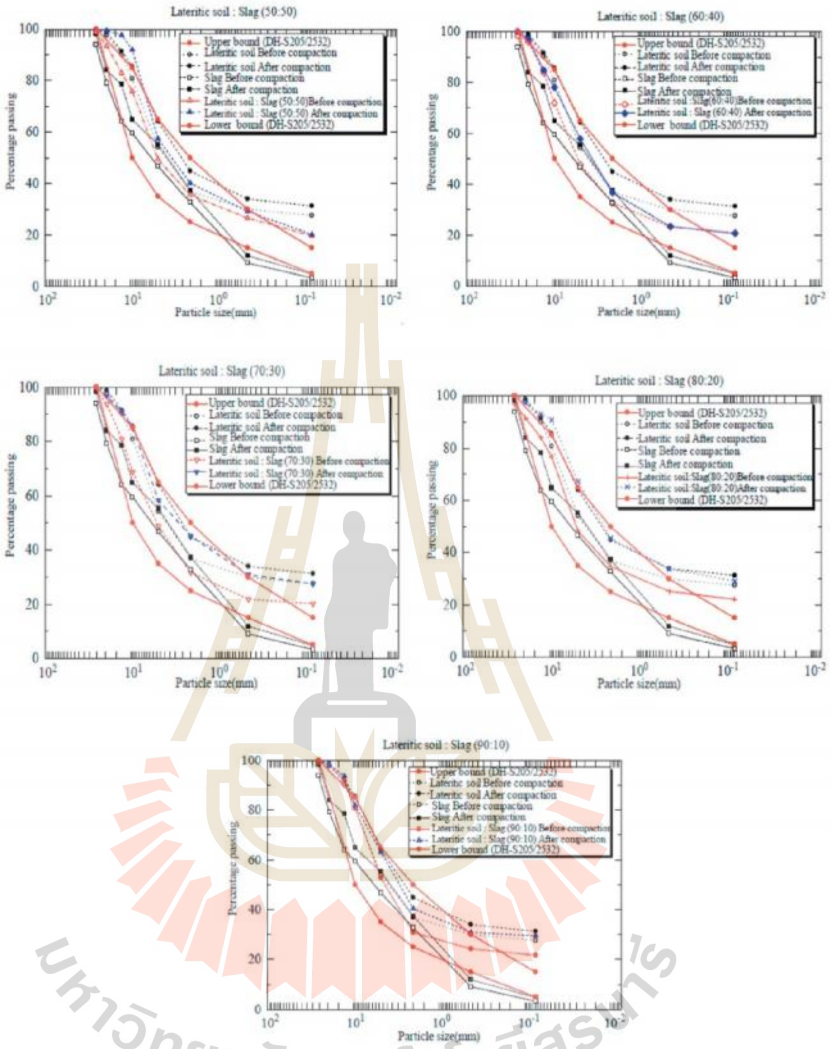


Fig. 2. Particle size distribution of lateritic soil/CS blends at 10–50% CS replacement.



the LS/CS blends. LA abrasion test was performed in accordance with ASTM C131-69 and C535-69. LA abrasion test is the most widely specified test for evaluating the resistance of aggregates to abrasion and impact forces (Papagiannakis and Masad, 2007).

The California bearing ratio (CBR) and swelling test methods were undertaken in accordance with AASHTO (1993). The CBR and swelling tests were carried out on blends subjected to modified Proctor compaction effort at the optimum water content and soaked for 4 days to simulate the worst-case scenario whereby the soil is fully saturated. For each CS replacement content, at least five samples were tested under the same conditions to ensure the reproducibility of the results. In most cases, the results under the same testing condition were reproducible with a low mean standard deviation, $SD$ ($SD/\bar{x} < 10\%$, where $\bar{x}$ is the mean strength value).

## 3. Results and discussion

### 3.1. Physical properties

The physical properties required for compacted materials according to Department of Highways, Thailand

Table 1
Physical properties of lateritic soil/CS blend.

| Sample description | CS | Lateritic Soil:CS | | | | | Lateritic soil | Remark |
|---|---|---|---|---|---|---|---|---|
| | | 50:50 | 60:40 | 70:30 | 80:20 | 90:10 | | |
| Bulk specific gravity Coarse-grained | 3.35 | 2.92 | 2.89 | 2.77 | 2.76 | 2.70 | 2.67 | AASHTO T85-70 |
| Bulk specific gravity Fine-grained | 3.54 | 3.20 | 3.21 | 3.21 | 3.22 | 3.21 | 3.03 | AASHTO 84 |
| Average specific gravity Coarse-Fine grained | 3.44 | 3.06 | 3.05 | 2.99 | 2.99 | 2.95 | 2.85 | |
| Apparent specific gravity Coarse-grained | 3.51 | 3.25 | 3.30 | 3.23 | 3.23 | 3.19 | 3.18 | AASHTO T85-70 |
| Apparent specific gravity Fine-grained | 4.26 | 3.72 | 3.71 | 3.72 | 3.73 | 3.70 | 3.47 | AASHTO 84 |
| Water absorption Coarse-grained | 1.34 | 3.41 | 4.34 | 5.06 | 5.27 | 5.68 | 5.95 | AASHTO T85-70 |
| Water absorption Fine- grained (%) | 4.79 | 4.30 | 4.26 | 4.28 | 4.20 | 4.18 | 4.19 | AASHTO 84 |
| LA abrasion value (%) | 17.2 | 42.3 | 46.2 | 47.58 | 48.2 | 51.18 | 58.1 | ASTM C131, C535 |
| LL (%) | – | 30.3 | 31.9 | 32.7 | 37.8 | 38.6 | 40.7 | AASHTO T90 |
| PL (%) | – | 20.2 | 21.7 | 21.2 | 20.4 | 20.4 | 20.9 | AASHTO T90 |
| PI (%) | – | 10.1 | 10.2 | 11.5 | 17.4 | 18.1 | 19.8 | |
| $D_{10}$ (mm) | 0.45 | – | – | – | – | – | – | |
| $D_{30}$ (mm) | 1.75 | 0.76 | 1.35 | 1.50 | 0.90 | 0.37 | 1.80 | |
| $D_{50}$ (mm) | 5.50 | 3.70 | 5.10 | 4.75 | 4.90 | 4.00 | 4.50 | |
| $D_{60}$ (mm) | 9.5 | 5.48 | 6.70 | 6.90 | 6.10 | 5.50 | 5.50 | |
| $C_u$ | 21.11 | – | – | – | – | – | – | |
| $C_C$ | 0.72 | – | – | – | – | – | – | |
| Gravel size content (%) | 53.3 | 50.6 | 50.3 | 49.2 | 48.5 | 48.0 | 47.3 | Retained #4 |
| Sand size content (%) | 43.4 | 32.0 | 31.2 | 31.6 | 31.0 | 31.6 | 31.0 | Passed#4-Retain#200 |
| Fines size content (%) | 3.3 | 17.4 | 18.5 | 19.2 | 20.5 | 20.4 | 21.7 | Passed#200 |
| Classification-USCS | GP | GC | GC | GC | GC | GC | GC | |

include water absorption, gradation, plasticity and Los Angles abrasion. The role of CS replacement on improving physical properties and the comparison of improved physical properties and requirement of Department of Highways is presented in this section. Table 1 presents the physical properties of LS/CS blends at various CS replacement contents. The relevant international standards for water absorption specify a different testing method to be followed for coarse-grained blends (AASHTO T 85-70) and for fine-grained blends (AASHTO T 84). The water absorption of the coarse-grained blends was determined from particles larger than 0.075 mm while the water absorption of the fine-grained blends was determined from particles smaller than 0.075 mm. The water absorption of coarse- and fine-grained CS differed significantly, indicating the fine-grained CS has higher water absorption potential. The same, however, was not true for LS: both coarse- and fine-grained LS had similar water absorption. The water absorption of coarse-grained CS (= 1.34%) was approximately 4.4 times lower than that of coarse-grained LS (= 5.95%) while the water absorption of fine-grained CS (= 4.79%) was slightly higher than that for fine-grained LS (= 4.19%). The lower water absorption of coarse-grained CS can be attributed to the lower water absorption potential of steel than soil in nature. Since the water absorption of the predominantly coarse-grained CS is very low, the water absorption of the CS is significantly lower than that of LS. As such, the water absorption values of coarse-grained LS/CS blends decreased with increasing CS replacement content while the water absorption values of fine-grained LS/CS blends increased slightly with increasing CS replacement content.

The grain size distribution parameters including $D_{10}$, $D_{30}$, $D_{50}$, $D_{60}$, $C_u$, $C_c$, and gravel, sand, fine contents and USCS symbols are summarized in Table 1. Fig. 2 shows the particle size distribution curves of LS/CS blends at CS replacement contents of 10%, 20%, 30%, 40%, and 50% compared with the upper and lower boundaries of base/sub-base materials specified by the Department of Highways, Thailand. As CS has larger particles than LS, the CS replacement result in a reduction in fine particles for the CS/LS blends. The smallest particles were found at 50% CS replacement.

Liquid limit (LL) and plasticity index (PI) are important factors that assist engineers and pavement designers to understand the consistency or plasticity of a soil, which is associated to the strength and deformation of the soil materials. As CS is classified as a non-plastic, coarse-grained material, when it is blended with LS, it reduces the plasticity of the marginal LS, as is evident in Table 1. The LL and PI values of the marginal LS gradually decrease from 40.7 to 30.3 and from 19.8 to 10.1, respectively when the CS replacements increase from 0% to 50%. It demonstrates that the LL and PI values of LS/CS blends met the consistency limits for subbase material (LL $\leq$ 35 and PI $\leq$ 11) specified by the Department of Highway, Thailand (DH-S, 1996). Moreover, with a relatively low LA abrasion of CS = 17.2% compared with that of LS = 58.1%, the CS replacement significantly improves the LA abrasion of the blends. The LA abrasion of LS decreases from 58.1% (for 0% CS replacement) to 42.3% (for 50% CS replacement). The LS/CS blends for all CS replacement proportions met the LA abrasion requirements of <60%, specified for subbase and engineering fill materials. While the particle size distribution of the LS/CS blend was not within the limits specified for base and sub-base materials, the requirements for an engineering fill material were met.

### 3.2. Compaction behavior

The modified compaction test results in Table 2 and Fig. 3 show that the blends at various CS replacement contents exhibit a bell-shaped compaction pattern, typical for geo-materials (Horpibulsuk et al., 2008, 2009). The compactive effort forces the soil and CS particles to move into the available pores by the expulsion of air and with the assistance of water lubrication. In other words, air is expelled by the compative effort and water facilitates the rearrangement of the soil and CS particles into a denser configuration. As a result, the dry density increase until the maximum dry density (MDD) is achieved at the optimum moisture content (OMC). After the attainment of the MDD, the compactive effort cannot expel any more air at water contents above the OMC. The excessive water then fills the pores and displaces the soil particles, thus decreasing the number of soil gains per unit volume of soil and consequently, decreasing the dry density.

The compaction curve for CS is more sensitive to water content than that of LS. The MDD value of the compacted CS is 26.9 kN/m$^3$, and is considerably higher than the MDD value = 21.6 kN/m$^3$ of the compacted LS, while the OMC = 7.25% of the compacted CS is slightly lower than the OMC = 7.6% of the compacted LS. The higher MDD of CS is due to the higher specific gravity. The bulk specific gravity of coarse-grained particles of CS and LS are 3.35 and 2.67, respectively. The MDD values of LS/CS blends were between those of the LS and CS, which are 21.6 kN/m$^3$, 21.7 kN/m$^3$, 22.6 kN/m$^3$, 23.4 kN/m$^3$ and 24.3 kN/m$^3$ for 10%, 20%, 30%, 40%, and 50% CS replacement, respectively. It is evident that CS replacement significantly increases the MDD of the blends from 21.6 kN/m$^3$ (for 0% CS replacement) to 24.3 kN/m$^3$ (for 50% CS replacement). The increase in CS replacement content increases not only the density but also the water sensitivity; i.e., a distinct peak is detected.

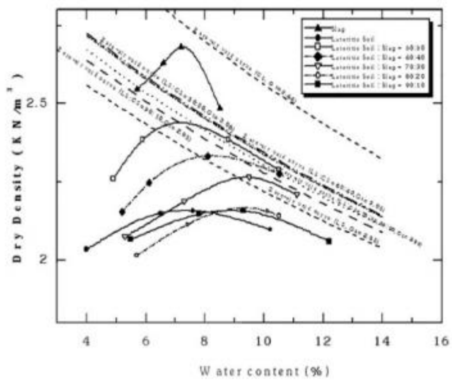


Fig. 3. Dry density versus moisture content relationship of lateritic soil/CS blends.

The compaction characteristics and the MDD values of LS/CS blends are almost the same even for CS replacements up to 20%. However, a significant increase in MDD is clearly noted when the CS replacement content is greater than 20%. The similar OMC values of LS and CS indicate that the variation of OMC of the blends with CS replacement was in a narrow band (from 7.6% to 9.65%). The OMC values of the LS/CS blends are 8.7%, 9.4%, 9.65%, 8.25%, and 7.25% for 10%, 20%, 30%, 40%, 50% CS replacement, respectively.

The effect of compaction effort on the particle breakage of LS, CS, and LS/CS blends is shown in Fig. 2. This effect was significant for LS particularly for particles smaller than 10 mm, while the particle breakage for CS was found to be insignificant. By comparing Tables 1 and 2, it is apparent that after compaction, the contents of the gravel-sized and

Table 2
Mechanical properties of compacted lateritic soil/CS blends.

| Sample description | CS | Lateritic soil:CS | | | | | Lateritic soil | Remark |
|---|---|---|---|---|---|---|---|---|
| | | 50:50 | 60:40 | 70:30 | 80:20 | 90:10 | | |
| Compaction (Modified):Max Dry Density (KN/m$^3$) | 26.9 | 24.3 | 23.4 | 22.6 | 21.7 | 21.6 | 21.6 | AASHTO T180 |
| Compaction (Modified):OMC (%) | 7.25 | 7.25 | 8.25 | 9.65 | 9.40 | 8.70 | 7.60 | AASHTO T180 |
| California Bearing Ratio (Soaked 4 days) (%) | 95 | 45 | 34 | 31 | 26.5 | 19 | 9.3 | AASHTO T193 |
| Swell (Soaked 4 days) (%) | 0 | 2.26 | 2.97 | 3.87 | 4.41 | 5.04 | 6.40 | AASHTO T193 |
| LL (%) | | 32.5 | 33.9 | 37.5 | 39.4 | 39.4 | 45.6 | AASHTO T90 |
| PL (%) | | 21.2 | 22.2 | 27.1 | 27.3 | 23.2 | 24.6 | AASHTO T90 |
| PI (%) | – | 11.3 | 11.7 | 10.4 | 12.1 | 16.2 | 21.0 | |
| $D_{10}$ (mm) | 0.27 | – | – | – | – | – | – | |
| $D_{30}$ (mm) | 1.30 | 0.45 | 0.92 | 0.29 | 0.09 | 0.18 | – | |
| $D_{50}$ (mm) | 3.80 | 3.25 | 3.45 | 2.75 | 2.40 | 2.80 | 2.50 | |
| $D_{60}$ (mm) | 7.00 | 4.95 | 5.10 | 4.80 | 3.50 | 4.25 | 4.00 | |
| ($D_{50}$(before)- $D_{50}$(after))/D50 (before) | 0.31 | 0.12 | 0.32 | 0.42 | 0.51 | 0.30 | 0.44 | |
| $C_u$ | 25.92 | – | – | – | – | – | – | |
| $C_C$ | 0.89 | – | – | – | – | – | – | |
| Gravel size content (%) | 44.8 | 42.6 | 42.2 | 41.6 | 39.7 | 36.9 | 35.8 | Retained #4 |
| Sand size content (%) | 50.4 | 37.2 | 37.1 | 30.8 | 31.1 | 33.6 | 32.9 | Passed#4-Retain#200 |
| Fines size content (%) | 4.8 | 20.2 | 20.7 | 27.6 | 29.2 | 29.5 | 31.3 | Passed#200 |
| Classification-USCS | SP | GC | GC | GM | GM | GC | GC | |

sand-sized particles of LS decreased due to the breakage of large particles by the compaction effort. This resulted in an increase in silt-sized and clay-sized particles; i.e., the coarse (gravel and sand) content decreased from 78.3% to 68.7% while the fines (silt and clay) content increased from 21.7% to 31.3% after compaction of the LS. Although the compaction effort caused the particle breakage of CS, it is noted that the coarse content of CS decreased only slightly from 96.7% to 95.2%. This is in agreement with the compaction results of CS in that the fines content of CS increased slightly from 3.3% to 4.8% after compaction. Furthermore, particle breakage resulted in a decrease in the gravel size content to about 8.5%, an increase of about 7% of sand size content, and only 1.5% of the fines size content. Consequently, the soil classification of CS changes from poorly-graded gravel (GP) to poorly-graded sands (SP). In contrast, the particles breakage of LS resulted in a decrease in the gravel size contents to about 11.5%; however, a raise of only 1.9% of sand size content was oberserved with 9.6% of fines size content. This indicates that the particle strength of CS was higher than that of LS. Due to the high particle strength of CS, CS replacement notably prevents the breakage of the coarse aggregate of LS and hence results in minimal reduction of the fines content. The soil classification of the blends before and after compaction was the same for 10% CS replacement.

### 3.3. California bearing ratio and swelling

Particle breakage causes an increase in fines content, hence the increase in liquid limit and plastic limit of LS and LS/CS blends after compaction. The LL and PI values of the LS after compaction increases from 40.7% to 45.6% and from 19.8% to 21.0%, respectively. Since the mechanical properties of the compacted materials are governed by the after-compaction physical properties, increased particle breakage results in inferior mechanical properties. In other words, CS replacement prevents particle breakage, hence resulting in the improvement of mechanical properties. This is represented by soaked CBR and swelling values.

Generally, the bearing capacity or CBR and swelling of compacted materials are controlled by the fines content. A higher fines content results in a higher water holding capacity, in which the water acts as a lubricant among the soil particles, and a lower bearing capacity or CBR. The test results for CBR and swelling at modified Proctor energy of the blends are shown in Table 3. The increase of CS replacement in LS/CS blends ws shown to reduce the fines content and water holding capacity and lead to the improvement of the CBR values. It is noted that the highest soaked CBR value of 95% was found for CS, while the lowest value, at 9.3%, was found for LS. In addition, the CBR values of LS/CS blends increased with increasing CS replacement; i.e., the CBR values of LS/CS ratio of 90:10, 80:20, 70:30, 60:40, and 50:50 were 19.0%, 26.5%, 3.10%, and 45.0%, respectively. Generally, higher swelling is associated with higher water absorption of fines content. The water absorption of LS decreased with increasing CS replacement (Table 1), resulting in decreased swelling. The swelling value at modified Proctor energy for 4 days soaked of CS was nominal. It is evident, as shown in Table 3, that the swelling value of LS/CS blends gradually decreased from 5.0% to 2.3% with increases in the CS replacement from 10% to 50%, respectively.

Fig. 4 shows the soaked CBR values at different compaction energy levels for various CS replacement contents in a semi-logarithm function. The results indicate that for a given CS replacement content, the soaked CBR values increased significantly with increased compaction energy ($E$). For a given compaction energy, the soaked CBR increased with the increased CS replacement proportion; i.e., the 100% CS replacement exhibits the highest soaked CBR for all $E$ values. The slope of all the blends increases with an increasing CS replacement content, indicating that the CS replacement improves the energy-sensitivity of the blends. With higher CS replacement, the soaked CBR development with compaction energy is larger.

Fig. 5 shows the swelling versus logarithm of $E$ relationship for various CS replacement contents. Unlike the soaked CBR versus logarithm of $E$ relationship, two types of relationship were found: bi-linear and linear. A bi-linear relationship was found when the CS replacement was <30%, and a change in the slope occurred at $E = 2681$ kJ/m$^3$ (modified Proctor energy). Steeper slopes werere observed at lower CS replacement contents, indicating that the compaction energy played a significant role on the swelling reduction when the CS was lower than 30%, particularly when $E > 2681$ kJ/m$^3$. By replacing LS with CS, the swelling was reduced as the CS replacement content increased. It is evident that both slopes of all the blends decreased with increasing CS replacement content.

Table 3
Mechanical properties of lateritic soil/CS blends compared with specification from Department of Highways, Thailand.

| Sample description | Base material (DH-S210/2547) | Sub-base material (DH-S205/2532) | Engineering fill material (DH-S208/2532) | CS | Lateritic soil:CS | | | | | Lateritic soil |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 50:50 | 60:40 | 70:30 | 80:20 | 90:10 | |
| LA abrasion value (%) | ≤ 40 | ≤ 60 | ≤ 60 | 17.2 | 42.3 | 46.2 | 47.6 | 48.2 | 51.2 | 58.1 |
| California Bearing Ratio (%) | ≥80 | ≥25 | ≥10 | 95.0 | 45.0 | 34.0 | 31.0 | 26.5 | 19.0 | 9.3 |
| Swell (%) | ≤0.5 | ≤4 | ≤3 | 0 | 2.3 | 3.0 | 3.9 | 4.4 | 5.0 | 6.40 |
| LL (%) | ≤25 | ≤35 | ≤40 | – | 30.3 | 31.9 | 32.7 | 37.8 | 38.6 | 45.6 |
| PI (%) | ≤4 | ≤11 | ≤20 | – | 10.1 | 10.2 | 11.5 | 17.4 | 18.1 | 21.0 |

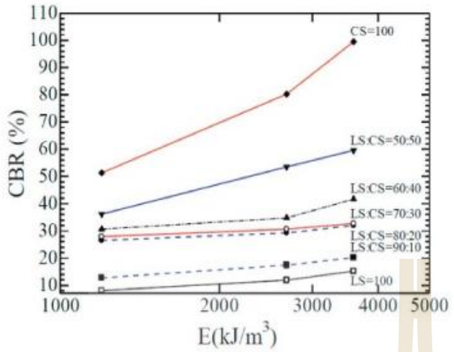


Fig. 4. Soaked CBR versus compaction energy relationship of lateritic soil/CS blends.

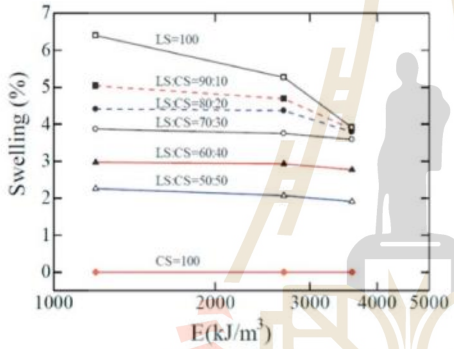


Fig. 5. Swelling versus compaction energy relationship of lateritic soil/CS blends.

In contrast to the present research, Akinwumi (2014) studied the soaked CBR of soil-slag blends with various slag contents of 5%, 8%, and 10% by total weight. It was reported that the soaked CBR values increased with increasing slag replacement content up to 10% slag replacement. Beyond this slag replacement content, the soaked CBR of the soil/slag blends was lower than that of the parent soil. Similarly, Yadu et al. (2013) demonstrated that the soaked CBR value of soil could be enhanced by slag replacement. However, its CBR values decreased when the slag replacement content was at 12%, as the bond strength between the soil and slag matrix was reduced due to the excess slag content. The experimental study on the utilization of steel slag stabilized high plastic subgrade soil by Aldeeky and Hattamleh (2017) also indicated that the CBR values of the soil-slag mixture increased with increasing slag replacement from 5% to 20% and then decreased at 25% of slag replacement. It is of interest to note that the CBR values of the previous studies increased and also decreased with the slag replacement, which contradicts the findings in this research in which the CBR values increased with increasing CS replacement contents from 0% to 50%. This can be attributed to the different types and gradations of slag; i.e., the particle size of CS is larger than that of LS in this research, whereas fine particles of slag were used as filler in the parent soil in the previous research. However, the swelling values were found to decrease with increasing slag replacement contents for both the previous research and the present study as slag has lower water absorption than natural soil.

Based on an analysis of soaked CBR and swelling test results in this research, it is practical to relate the soaked CBR and swelling of blends at various compaction energies in terms of CS replacement content as the improvement rate of CBR and swelling with CS replacement content is marginally dependent upon $E$. The predictive equations for soaked CBR and swelling in terms of CS replacement content (Figs. 6 and 7) are presented as follows:

$$\frac{CBR_{CS}}{CBR_0} = 1.0\exp(0.030CS) \quad \text{for } 1197\ \text{kJ/m}^3 < E < 3591\ \text{kJ/m}^3 \tag{1}$$

$$\frac{S_{CS}}{S_0} = 1.0\exp(-0.016CS) \quad \text{for } 2681\ \text{kJ/m}^3 < E < 3591\ \text{kJ/m}^3 \tag{2}$$

where $CBR_{CS}$ and $CBR_0$ are the soaked CBR at different CS replacement contents (ranging from 0% to 50%) and soaked CBR at 0% CS replacement, respectively and $S_{CS}$ and $S_0$ are the swelling at different CS replacement contents (ranging from 0% to 50%) and swelling at 0% CS replacement, respectively. These predictive equations are useful for predicting soaked CBR and swelling at different CS replacement contents based on the values of LS (without CS replacement).

The CBR and swelling data from the previous studies on various types of soil/CS blends are presented and compared with the present data in Figs. 6 and 7. Fig. 6 demonstrates that tan exponential relationship can be used to fit the test data (for those increase with increasing slag replacement

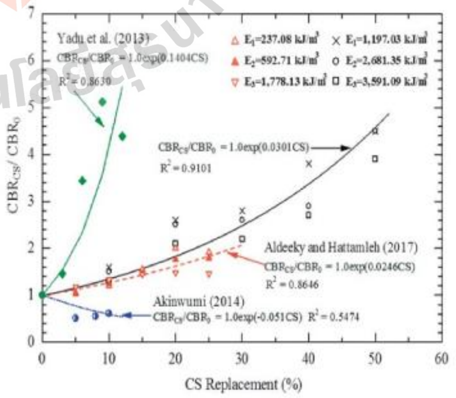


Fig. 6. Normalized soaked CBR versus compaction energy relationship of lateritic soil / CS blends.

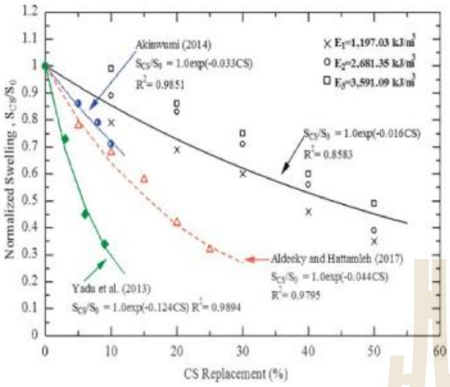


Fig. 7. Normalized swelling versus compaction energy relationship of lateritic soil/CS blends.

content) of different soil/CS blends, but the equations are different. Fig. 6 indicates that the proposed equation generated from the CBR data in this research is in good agreement with data reported by Aldeeky and Hattamleh (2017), even though it is slightly higher when the CS replacement content is greater than 15%. This is because Aldeeky and Hattamleh (2017) used a high plasticity clay (CH) with a slag that was classified as a well-graded sand (SW), which is comparable to the granular materials used in this study. With the same trend, however, the proposed equation overestimates the data from Akinwumi (2014). While trends observed for the data from Yadu et al. (2013) differ considerably, and the proposed equation underestimated the data. The reason for this is that Akinwumi (2014) used a soil which contained approximately 50% of fines, with a high percentage of sand, which is classified as A-7-6(5) according to AASHTO (2008) and a slag with 75% passing through the 75 μm sieve opening. Yadu et al. (2013) on the other hand used an inorganic fine grained expansive soft soil with the classification of A-7-5(4) and with very fine slag particles. Fig. 7 shows that the normalized swelling, $S_{CS}/S_0$ for all swelling data decreased with increasing CS replacement. However, the proposed normalized swelling equation in this research was found to overestimate the data from previous studies, as the water absorption for the larger CS particles used in this research was lower water than that of the fine slag particles used in the previous studies.

As evident in Figs. 6 and 7, the formulation of the predictive equations are based on sound principles and Eqs. (1) and (2) are applicable for the LS/CS blends studied and other similar materials that were within the gradation requirement specified by Department of Highways and Department of Rural Roads, Thailand. The proposed exponential relationship can be used to develop a generalized equation for various soil/CS with different gradation for future studies.

Table 3 summarizes the physical and mechanical properties of the blends at various CS replacement contents compared with the requirements for engineering fill, subbase and base materials specified by the Department of Highways, Thailand. It is evident that the marginal LS has a lower soaked CBR and higher swelling and LL than the requirements for an engineering fill material. The CS replacement can improve the unfavorable mechanical properties of LS. With over 10% CS replacement, the physical and mechanical properties of the blends meet the requirements for engineering fill materials. The higher CS replacement content results in better mechanical properties, hence the higher stability of the pavement structure with a thinner subbase and base courses.

The present study on the improvement of marginal lateritic soil by CS replacement has significant impacts on future pavement construction methodology. Field construction can begin by roller-compacting the underlying subgrade in accordance with the specifications of the road authority. Marginal lateritic soil can next be mixed with CS at the construction site or ready mixed at an external plant. A mixture of lateritic soil and CS can then be compacted to attain a minimum of 95% modified Proctor density. Finally, the field density and CBR of the pavement samples can be measured for quality control purposes.

## 4. Conclusions

Marginal lateritic soil (LS) improvement by crushed slag (CS) replacement has been evaluated in this research. The laboratory evaluation includes physical properties (particle size distribution, Atterberg limits and LA abrasion) and mechanical properties (CBR and swelling). The following conclusions can be drawn from this study:

1. CS improves both the physical and mechanical properties of marginal LS. Because CS is a non-plastic and coarse-grained material, the liquid limit and plasticity index of LS reduce with increasing CS replacement contents. Based on the low LA abrasion loss values (17.3%) of CS, CS replacement enhances the durability against traffic load to the marginal LS.
2. Compaction breaks down the coarse grains of the LS, which results in an increase in fines content. With higher abrasion resistance, the CS replacement improves the particle breakage due to compaction, resulting in a lower fines content. This lower fines content of compacted blends with higher CS replacement contents increases the soaked CBR and decreases swelling.
3. With the low water absorption of CS, both the water absorption and swelling of blends decrease with increased CS replacement. The rate of soaked CBR development and swelling reduction with CS replacement is essentially similar for all *E* values tested. Consequently, predictive equations for soaked CBR and swelling in term of CS replacement are proposed for various *E* values, which are useful for geotechnical and pavement practitioners. The soaked CBR and swelling of blends at various CS replacement contents

and $E$ values can be predicted once the soaked CBR and swelling of LS (without CS) are known. The formulation of the proposed equations is based on soil mechanics principles and can be extended to other types of marginal soils.

4. CS replacement improves the mechanical properties of the original parent material and meets the requirements for an engineering fill material, as defined by the Department of Highways, Thailand. In this research, the CS traditionally destined for landfill is found to be suitable as a replacement material to stabilize LS and also as a sustainable engineering fill material. With a minimum 10% CS replacement content, the physical and mechanical properties of blends meet the requirements for engineering fill materials.

## Acknowledgments

This work was supported by the Thailand Research Fund under the TRF Senior Research Scholar program Grant No. RTA5980005 and Suranaree University of Technology. The authors would like to acknowledge the facility, laboratory and equipment provided by Bureau of Highways 3 (Sakonnakhon), Department of Highways, Thailand.

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