# ENGINEERING PROPERTIES AND ENVIRONMENTAL IMPACT ASSESSMENT OF MARGINAL LATERITIC SOIL IMPROVED BY MELAMINE DEBRIS REPLACEMENT FOR SUSTAINABLE PAVEMENT APPLICATION

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

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# คุณสมบัติทางวิศวกรรมและการประเมินผลกระทบทางสิ่งแวดล้อมของดินลูกรังด้อยคุณภาพที่ปรับปรุงคุณภาพโดยใช้เศษครีบเมลามีนแทนที่เพื่อใช้ในงานทางอย่างยั่งยืน

นายจีรพรรณ ดลรักษ์



วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต
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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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จีรพรรณ คลรักษ์ : คุณสมบัติทางวิศวกรรมและการประเมินผลกระทบทางสิ่งแวดล้อมของดิน ลูกรังด้อยคุณภาพที่ปรับปรุงคุณภาพโดยใช้เศษครีบเมลามีนแทนที่เพื่อใช้ในงานทางอย่างยั่งยืน (ENGINEERING PROPERTIES AND ENVIRONMENTAL IMPACT ASSESSMENT OF MARGINAL LATERITIC SOIL IMPROVED BY MELAMINE DEBRIS REPLACEMENT FOR SUSTAINABLE PAVEMENT APPLICATION) อาจารย์ที่ปรึกษา : ศาสตราจารย์ ดร.สุขสันติ์ หอพิบูลสุข, 103 หน้า.

วิทยานิพนธ์นี้มีวัตถุประสงค์ที่จะศึกษาความเป็นไปได้ในการใช้เศษครีบเมลามีนเพื่อปรับปรุงคุณภาพของดินลูกรังด้อยคุณภาพ ให้สามารถนำมาใช้เป็นวัสดุงานโครงสร้างทางอย่างยั่งยืน โดยวิทยานิพนธ์ประกอบด้วย 3 ส่วนได้แก่ ส่วนแรกทำการทดสอบในห้องปฏิบัติการทางวิศวกรรมปฐพี โดยเตรียมอัตราส่วนผสมของตัวอย่างที่ผสมดินลูกรังด้อยคุณภาพต่อเศษครีบเมลามีน ในอัตราส่วนต่างๆ โดยน้ำหนัก (50/50, 60/40, 70/30, 80/20 และ 90/10) เพื่อใช้เป็นแนวทางในการใช้เป็นวัสดุทางเลือกที่ใช้ในการก่อสร้าง ชั้นรองพื้นทาง และชั้นพื้นทาง การทดสอบประกอบไปด้วยการหาขนาดคละ, ค่าความถ่วงจำเพาะ, ค่าการดูดซึมน้ำ, ค่าความต้านทานการสึกหรอ, การบดอัดแบบสูงกว่ามาตรฐาน และแคลิฟอร์เนียร์แบริ่งเรโช (CBR) ผลการทดสอบพบว่าเศษเมลามีนเป็นวัสดุที่ไม่มีความเหนียว (non-plastic) และมีความทนทานสูง ดังนั้น ดินลูกรังด้อยคุณภาพที่มีเศษครีบเมลามีนผสม จึงสามารถพัฒนาคุณสมบัติด้านการลดความเหนียว, เพิ่มความคงทนต่อการสึกหรอ, เพิ่มค่าแคลิฟอร์เนียร์แบริ่งเรโช และลดการบวมตัว ผลการทดลอบยังแสดงให้เห็นว่าคุณสมบัติทางกายภาพและคุณสมบัติทางกล ของดินลูกรังด้อยคุณภาพที่ถูกแทนที่ด้วยเศษครีบเมลามีนปริมาณร้อยละ20 สามารถนำมาใช้เป็นวัสดุคัดเลือกตามมาตรฐานกรมทางหลวง ในขณะที่ ดินลูกรังด้อยคุณภาพที่ถูกแทนที่ด้วยเศษครีบเมลามีนปริมาณ ร้อยละ 50 พบว่าอยู่ในเกณฑ์ใช้เป็นวัสดุรองพื้นทาง

ส่วนที่สองศึกษาความหนาแน่น ความสามารถในการรับแรงอัด และความทนทานต่อการทดสอบเปียกสลับแห้ง ของตัวอย่างดินลูกรังที่ผสมเศษครีบเมลามีนและปริมาณปูนซีเมนต์ที่อัตราส่วนต่างๆ ผลการศึกษาพบว่าความหนาแน่นและความสามารถในการรับแรงอัดลดลงตามปริมาณเศษครีบเมลามีนที่แทนที่เข้าไปอย่างมีนัยสำคัญ ถึงแม้ว่าความสามารถในการรับแรงอัดจะลดลง แต่ค่าแคลิฟอร์เนียร์แบริ่งเรโชแบบแช่และค่าความทนทานต่อการทดสอบเปียกสลับแห้ง มีค่าเพิ่มขึ้นตามปริมาณเศษครีบเมลามีน โดยอัตราส่วนที่เหมาะสมที่สุดจากการศึกษาพบว่าเท่ากับร้อยละ 20 ซึ่งสอดคล้องกับค่าแคลิฟอร์เนียร์แบริ่งเรโชแบบแช่ และความสามารถในการรับแรงอัดหลังการทดสอบเปียกสลับแห้ง ดินลูกรังที่แทนที่ด้วยเศษครีบเมลามีนร้อยละ 20 และปริมาณ

ปูนซีเมนต์ร้อยละ 3 อยู่ในเกณฑ์ใช้เป็นวัสดุคันทาง ในขณะที่ ดินลูกรังที่แทนที่ด้วยเศษครีบเมลามีนร้อยละ 40 และ20 ผสมปูนซีเมนต์ร้อยละ 5 อยู่ในเกณฑ์ใช้เป็นวัสดุชั้นรองพื้นทาง และชั้นพื้นทางตาม มาตรฐานกรมทางหลวงตามลำดับ ผลการทดสอบเปียกสลับแห้งพบว่าตัวอย่างที่ผสมเศษครีบเมลามีนสามารถทนทานต่อการทดสอบมากกว่า 3 วงรอบ

ส่วนท้ายของวิทยานิพนธ์ประเมินผลกระทบด้านสิ่งแวดล้อม โดยศึกษาความสามารถในการชะละลายโลหะหนักของตัวอย่างดินลูกรังที่ผสมเศษครีบเมลามีนและปริมาณปูนซีเมนต์ และและเปรียบเทียบกับมาตรฐานสากล ผลการศึกษาการชะละลายโลหะหนักพบว่าดินลูกรังที่แทนที่ด้วยเศษครีบเมลามีนร้อยละ 20 และปริมาณปูนซีเมนต์ร้อยละ 5 สามารถใช้ในงานโครงสร้างทางได้อย่างปลอดภัยเนื่องจากเนื่องจากความเข้มข้นของโลหะหนักที่ชะละลายอยู่ในช่วงที่ยอมรับได้ ผลของการศึกษาครั้งนี้จะเป็นการส่งเสริมให้มีใช้เศษครีบเมลามีนซึ่งเป็นวัสดุเหลือใช้ในงานก่อสร้างโครงทางที่เป็นมิตรต่อสิ่งแวดล้อมต่อไป



สาขาวิชาวิศวกรรมโยธา

ปีการศึกษา 2560

ลายมือชื่อนักศึกษา______________

ลายมือชื่ออาจารย์ที่ปรึกษา______________

JEERAPAN DONRAK : ENGINEERING PROPERTIES AND ENVIRONMENTAL IMPACT ASSESSMENT OF MARGINAL LATERITIC SOIL IMPROVED BY MELAMINE DEBRIS REPLACEMENT FOR SUSTAINABLE PAVEMENT APPLICATION. THESIS ADVISOR : PROF. SUKSUN HORPIBULSUK, Ph.D., 103 PP.

MARGINAL LATERITIC SOIL / MELAMINE DEBRIS / CEMENT / LEACHATE

This thesis aims to study the possibility of using melamine debris (MD) to stabilize marginal lateritic soil to be a sustainable stabilized pavement material. The thesis is mainly composed of three main parts. In this first part, a comprehensive suite of geotechnical laboratory tests was undertaken on samples of melamine debris (MD) blended with marginal lateritic soil (LS) at various ratios (50/50, 60/40, 70/30, 80/20 and 90/10) to ascertain it as an alternative unbound sub-base/base 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 MD is a non-plastic and durable material, the MD replacement improves soil plasticity, abrasion, CBR and swelling of the marginal lateritic soil. The results indicate that physical and mechanical properties of the 20% MD replacement blend are found to meet the requirement of local road authority for engineering fill materials while the 50% MD replacement blend is found to be at the borderline for subbase course material

The second part investigates the density, unconfined compression strength (UCS) and durability against wetting and drying (w-d) cycles of cement stabilized

LS/MD blends, at various cement contents and MD replacement ratios. The density and UCS of stabilized LS/MD blends decreases significantly with the MD replacement ratio. Even with the decrease in UCS, the soaked CBR and durability against w-d cycles are improved by MD replacement. The optimum MD replacement ratio is found to be 20%, which corresponds with the highest soaked CBR and w-d cycled UCS. The 3% cement LS/MD blend at 20% MD can be used as a stabilized subgrade material, while 5% cement LS/MD blends at 40% MD and 20% MD can be used as stabilized subbase and base materials, respectively based on the specification of Department of Highways, Thailand. These stabilized materials were found to sustain up to 3 w-d cycles.

Last, the environmental assessment, the leachability of the heavy metals of cement stabilized LS/MD blends were measured and compared with international standards. The leachate results indicated that 5% C LS/20%MD blend can be safely used in sustainable pavement applications, as the leachate heavy metal concentrations were within the acceptable range. The outcome of this study will promote the usage of waste MD in an environmentally friendly pavement construction manner.



School of Civil Engineering　　　Student's Signature______

Academic Year 2017　　　Advisor's Signature______

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Jeerapan Donrak

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# SYMBOLS AND ABBREVIATIONS

| | | |
|---|---|---|
| AASHTO | = | American Association of State Highway and Transportation official |
| $Al_2O_3$ | = | aluminum oxide |
| ASTM | = | American Society for Testing and Material |
| BDL | = | below detection limit |
| C | = | Portland cement |
| C&D | = | construction and demolition |
| CaO | = | calcium oxide |
| CBR | = | California Bearing Ratio |
| DOH | = | department of highway |
| $E$ | = | compaction energy |
| EPA | = | environmental protection agency |
| $Fe_2O_3$ | = | hematite |
| $K_2O$ | = | potassium oxide |
| kPa | = | kilo Pascal |
| LA | = | Los Angeles abrasion test |
| LOI | = | loss of ignition |
| LS | = | marginal lateritic soil |
| MD | = | melamine debris |
| MDD | = | maximum dry density |

# SYMBOLS AND ABBREVIATIONS (Continued)

| | | |
|---|---|---|
| MgO | = | magnesium oxide |
| $Na_2O$ | = | sodium oxide |
| N.D | = | not detected |
| NS | = | not specified. |
| $°2\theta$ | = | 2 theta |
| °C | = | degree Celsius |
| OMC | = | optimum moisture content |
| pH | = | potential of Hydrogen ion |
| SEM | = | scanning electron microscopy |
| $SiO_2$ | = | silicon dioxide |
| $SO_3$ | = | sulfur trioxide |
| TCLP | = | Toxicity characteristic leaching procedure |
| UCS | = | unconfined compression strength |
| USCS | = | unified soil classification system |
| WC | = | water content |
| w-d | = | wetting-drying |
| XRD | = | X-ray diffraction |
| XRF | = | X-ray fluorescence |

# CHAPTER I

# INTRODUCTION

## 1.1 Statement of problem

Presently quality materials used for pavement structure were greatly reduced due to being used continuously. When no suitable materials are available and it is expensive to bring the materials from distant sources, an alternative way, which is commonly used in practice, is to replace the locally available soil by quality materials. For economical and environmental impacts, the replacement by waste materials has been recently performed (Arulrajah et al., 2014a and b).

The stockpile of waste materials generated by the everyday activities of a growing population has become a persistent problem, which is furthermore exacerbated by the lack of available technologies to adequately treat or dispose of these waste materials (Ribeiro de Rezende et al., 2014). Several authors have researched on the utilization of various recycled materials in geotechnical and pavement applications. The usage of recycled materials to stabilize marginal soils has significant economical and environmental impacts and has been recently performed (Arulrajah et al., 2014a and b; Kampala and Horpibulsuk, 2013; Kampala et al., 2013 and Phetchuey et al., 2014). This includes 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 used with geotextile 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) and crushed brick as supplementary material in bound pavement (Disfani et al., 2014). The utilization of these recycled materials has a significant impact on the sustainability of our scarce natural resources and the reduction of construction and industrial wastes.

Industrial wastes resulting from the rapid development in developed and developing countries is the prime factor responsible for environmental degradation. The recycling of industrial waste materials has consolidated its presence as an efficient mechanism to minimize the problems arising from the wastes generated by anthropic activities (Ribeiro de Rezende et al., 2014).

Melamine debris (MD) is a waste material resulting from plate and cup manufacture. This MD cannot be reformed or reused for manufacturing plates and cups (Siwadamrongpong et al. 2012). Presently, this MD is disposed by burning at a very high temperature, which damages the air environment and is furthermore costly. The sustainable usage of MD in civil engineering applications will provide lower a carbon footprint and result in positive social and economical impacts for governments, industry and consumers.

The usage of MD 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 material. This thesis attempts to study the possibility of using the melamine debris for pavement applications as unstabilized and stabilized materials. The environmental assessment of both materials will be finally evaluated to ascertain them as a sustainable pavement material. The research is this significant in term of engineering, economical and environmental perspectives.

## 1.2 Research objectives

The main objectives of this study are as below:

1.2.1 To investigate a possibility of using MD as replacement material to improve the mechanical properties of marginal lateritic soil.

1.2.2 To evaluate the mechanical and durability properties of cement stabilized melamine debris/marginal lateritic soil blends.

1.3.3 To investigate the environmental assessment of MD/marginal lateritic soil blends with cement stabilization to ascertain them as green pavement materials.

## 1.3 Structure of presentation

This thesis consists of six chapters and outlines of each chapter are presented as follows:

**Chapter I** presents the introduction of study.

**Chapter II** presents the review of previous research on waste materials, waste materials in geotechnical engineering , existing research and summary of previous researchers.

**Chapter III** presents the physical and mechanical properties of marginal lateritic soil replaced by MD as a sustainable engineering fill material. The laboratory evaluation program includes physical properties (specific gravity, water absorption, Atterberg limits, and particle-size distribution tests) and mechanical properties (modified Proctor compaction, Los Angeles abrasion, and California Bearing Ratio (CBR) tests).

**Chapter IV** presents the environmental impact assessment, density, strength and durability against wetting and drying (w-d) cycles of cement stabilized LS/MD blends. The strength change with the MD replacement is illustrated the mineralogical and microstructural changes using the application of X-ray diffraction (XRD) and scanning electron microscopy (SEM) analyses. The change in the strength and physical properties of cement stabilized LS/MD blends at various cyclic w–d cycles were examined using unconfined compression strength (UCS) and weight loss tests.

**Chapter V** presents the conclusion of each chapter and overall conclusion. The suggestion for further study is also presented in this chapter

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# CHAPTER II

# LITERATURE REVIEW

## 2.1 General

Over the last few years, environmental and economic issues have stimulated interest in the development of alternative materials that can fulfill design specifications. The well established techniques of soil stabilization and soil reinforcement are often used to obtain improved geotechnical materials through either the addition to soil of cementing agents (lime, Portland cement, asphalt, etc.) or the inclusion of oriented or randomly distributed discrete elements such as fibers and tire chips. Stabilized and reinforced soils are, in general, composite materials that result from combination and optimization of the properties of individual constituent materials (Cesar Consoli et al., 2014). 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 project might be cheaper. To increase and enhance the utilization of waste materials, the extensive study has widely investigated the possibility of usage of waste materials for various applications. This thesis investigated the physical and geotechnical properties of melamine debris for pavement applications.

## 2.2 Waste materials

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).

Plastic is an excellent and a very useful material to replace ceramic, wood and metals because it is very functional, cheap, hygienic, light and economic. The global production of plastic, therefore, has grown sharply over recent years. The increase in plastic consumption is largely responsible for the increase in solid wastes, and it has a great impact on their management (Derraik, 2002; Al-Salem et al., 2009).

Plastics can be separated into two types. The first type is thermoplastic, which can be melted for recycling in the plastic industry. These plastics are polyethylene, polypropylene, polyamide, polyoxymethylene, polytetrafluorethylene, and polyethyleneterephthalate. The second type is thermosetting plastic. This plastic cannot be melted by heating because the molecular chains are bonded firmly with meshed crosslinks. These plastic types are known as phenolic, melamine, unsaturated polyester, epoxy resin, silicone, and polyurethane (Panyakapo and Panyakapo., 2008). Melamine formaldehyde resin is one of the most common thermosetting plastics used for table wares (Siwadamrongpong, et al., 2012).

## 2.3 Waste materials in geotechnical engineering

The study on evaluation of used fine quarry wastes in the midwest region of Brazil for pavement construction. An experimental test asphalt pavement was built with conventional materials and a soil fine quarry waste mixture. Field tests were conducted to assess the behavior of these materials. It was verified that this waste is able to provide the same performance levels for low volume roads while offering environmental and economic advantages (Ribeiro de Rezende et al., 2014).

Cesar Consoli et al. (2014) reported that the unconfined compression tests, splitting tensile tests, and saturated drained triaxial compression tests with local strain measurement were carried out to evaluate the benefit of utilizing randomly distributed polyethylene terephthalate fiber, obtained from recycling waste plastic bottles, alone or combined with rapid hardening Portland cement to improve the engineering behavior of a uniform fine sand. The separate and the joint effects of fiber content (up to 0.9 wt%), fiber length (up to 36 mm), cement content (from 0 to 7 wt% , and initial mean effective stress (20, 60, and 100 kN/m$^2$) on the deformation and strength characteristics of the soil were investigated using design of experiments and multiple regression analysis. The results show that the polyethylene terephthalate fiber reinforcement improved the peak and ultimate strength of both cemented and uncemented soil and somewhat reduced the brittleness of the cemented sand. In addition, the initial stiffness was not significantly changed by the inclusion of fibers.

Mazumder et al. (2006) investigated the the feasibility of utilizing these overburnt bricks as coarse aggregates in highway pavement projects was explored. Routine laboratory tests such as the Los Angeles abrasion, water absorption, specific gravity, and unit weight, were used to compare the properties of the overburnt bricks with the best possible quality picked bricks from the same stockyards in Bangladesh. It was found that overburnt brick aggregates are much stronger, less absorptive, and denser in general than the ones from the picked bricks. Therefore, these bricks may be conveniently and economically used as highway pavement coarse aggregates.

Arulrajah et al. (2013) focused on the the possible application of recycled crushed glass blended with crushed basaltic waste rock as a footpath base material.

A field demonstration footpath comprising two sections of recycled glass waste rock blends with 15% and 30% recycled glass content and a third control section with only waste rock was subsequently constructed on the basis of the outcomes of the initial laboratory tests. Subsequently field tests with a nuclear density gauge and Clegg impact hammer were undertaken, as well as laboratory testing of field samples to assess the geotechnical performance of the trial sections. The field and laboratory test results indicated that adding crushed glass may improve the workability of the crushed waste rock base material but subsequently results in lower shear strength. The research findings indicate that recycled crushed glass in blends with crushed waste rock is a potential alternative material to be used in footpath bases.

Arulrajah et al. (2014) focused on engineering properties of highly organic materials have been undertaken to determine their engineering properties when used as road embankment fill materials. A prime contributor of organic wastes in municipal landfills is spent coffee grounds from cafes and domestic households. As part of this research, an extensive suite of engineering and environmental tests were undertaken on spent coffee grounds obtained from several popular cafes in Melbourne, Australia to evaluate their properties and potential use as a non-structural fill material in road embankments. From an environmental perspective, coffee grounds were found to pose no environmental and leaching issue for use as an embankment fill material. From an engineering material perspective, the high organic content, low maximum dry densities and high optimum moisture content restricts the usage of this material to non-structural fill applications where the material will not have to sustain high traffic loadings. The usage of spent coffee grounds as non-structural fill material in embankments was found to be a viable end-of-life option to divert coffee grounds from landfills and furthermore to maximize the naturally high organic content present in the coffee grounds for vegetation purposes.

Rahman et al. (2015) investigated the suitability of recycled construction and demolition (C&D) materials as alternative subbase materials for permeable pavements. Permeable pavements are increasingly being used as urban storm water management systems. Three commonly found recycled C&D waste materials, crushed brick (CB), recycled concrete aggregate (RCA), and reclaimed asphalt pavement (RAP), were investigated to assess their suitability as permeable pavement subbase materials. Geotextile was also used in this research to trap pollutants.. It was found that the geotextile layer did not have any effect in terms of permeability of the C&D materials. The chemical assessment included organic content, pH value, trace element, and leachate concentration for a range of contaminant constituents and compared with maximum allowable limits in soil and natural water as well as with the environmental protection authorities' requirements. In terms of geotechnical and chemical assessment for permeable pavement applications, RCA was found to be a suitable alternative construction material for permeable pavements, while CB was borderline and RAP did not meet some of the specified requirements

Edeh et al. (2014) presents the results of a laboratory evaluation of the characteristics of lateritic soil (LS) stabilized with sawdust ash (SDA), subjected to British standard light (BSL) compactive effort to determine their index, compaction, unconfined compressive strength (UCS), and California Bearing Ratio (CBR) results. The results of the laboratory tests show that the properties of LS improved when stabilized with SDA. The particle-size distribution improved from poorly graded, sandy, gravelly material for 100% lateritic soil and silty material for 100% SDA to the gradation with 94.9–99.9% coarse aggregates of sand and gravel, described as gravelly sand and sandy gravel material for SDA-stabilized LS. The CBR results obtained from the study show that, using the Nigerian general specifications, the maximum CBRs of 19.4% (soaked for 24 h) and24.1% (unsoaked) achieved for the mix proportion (70% LS + 30% SDA), which falls under American highway and transportation industry standards, can be used as subgrade material.

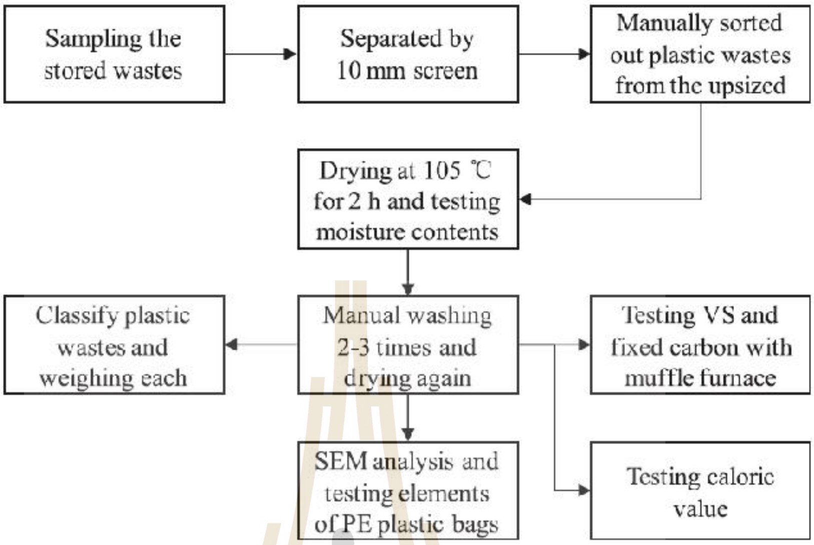
Kampala and Horpibulsuk (2013) presented basic and engineering properties of the recycled Calcium Carbide Residue (CCR) stabilized clay. For the same compaction energy and CCR content, the unit weight of the recycled CCR stabilized clay is lower than that of the CCR stabilized clay because the harder 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

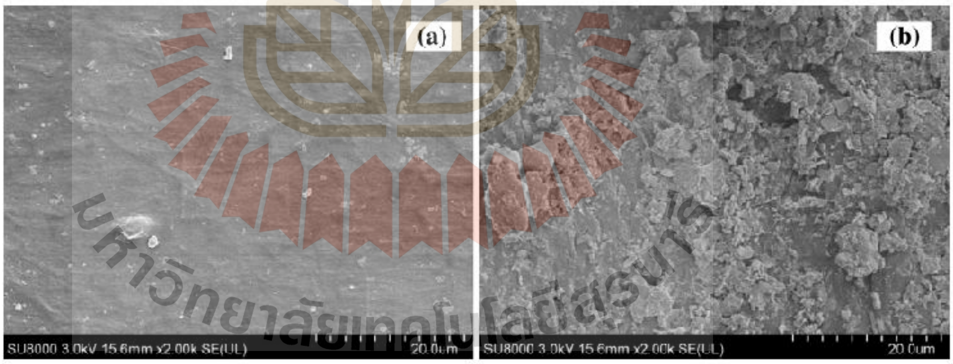
Amadi and Agapitus (2013) reported that the bentonite mixtures are finding wide application as buffer material for waste repositories for their favorable self-sealing qualities. The swelling properties of such materials which serve as a measure of their self-sealing capabilities and, thus, the efficiency of the repository in sealing off their contents from the environment are closely related to the chemistry of the leachate that emanate from the wastes. Experimental results showed that swelling potential based on thefree swell together with the maximum swell pressures of compacted soil mixtures measured at equilibrium increased approximately linearly with increase in the amount of bentonite when inundated with processed tap water and the three leachate solutions. On the other hand, these swelling parameters decreased as the ionic strength of the leachate solutions measured by their electrical conductivity increased for the various soil mixtures. These results provide an insight into the swelling behavior and the possible degradation in the efficiency of the proposed lateritic soil– bentonite mixtures in relation to their use as buffer material in waste landfills.

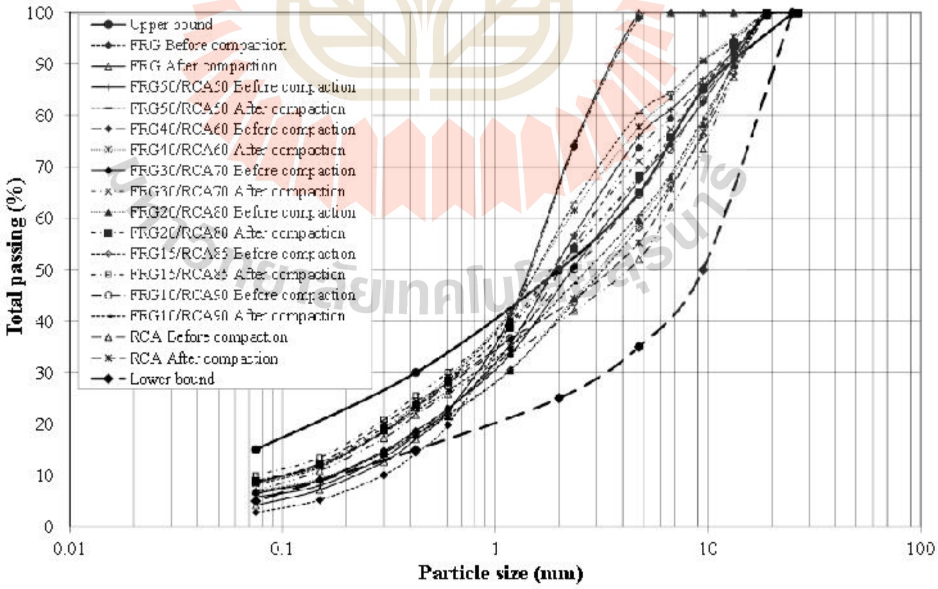


## 2.4 Existing research

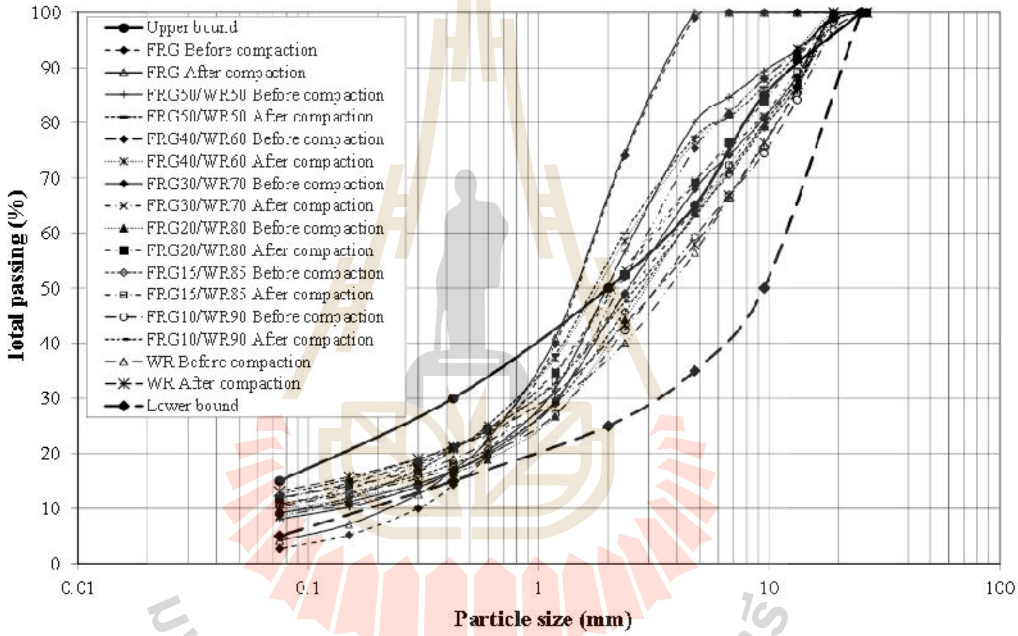
Zhou et al. (2014) focused on the characteristics of the landfill mined plastic wastes and their recovery potential was the key points to determine the feasibility of landfill mining projects. They were collected municipal solid waste samples of different storage years from the landfill and did mechanical screening and manual separating to

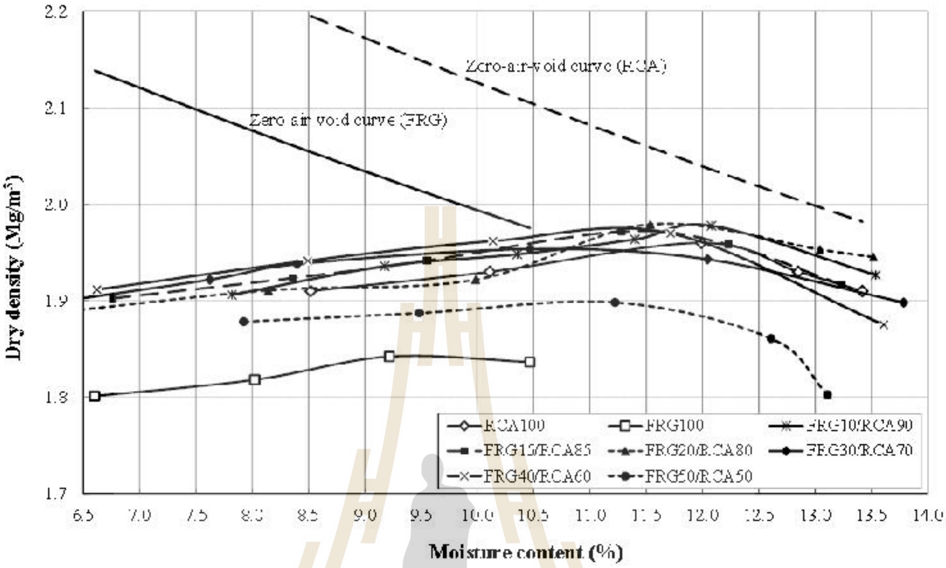

Sampling the stored wastes
Separated by 10 mm screen
Manually sorted out plastic wastes from the upsized
Drying at 105 ℃ for 2 h and testing moisture contents
Classify plastic wastes and weighing each
Manual washing 2-3 times and drying again
Testing VS and fixed carbon with muffle furnace
SEM analysis and testing elements of PE plastic bags
Testing caloric value

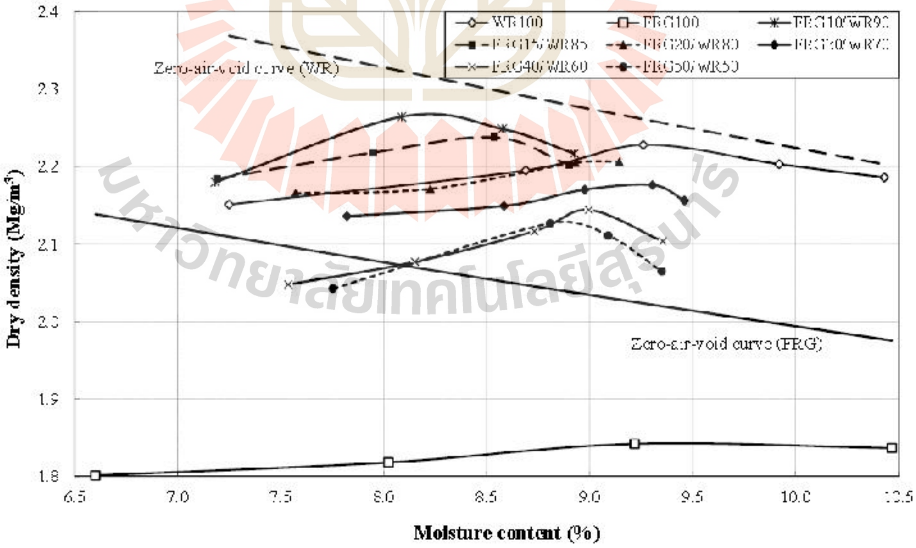

(a)
(b)

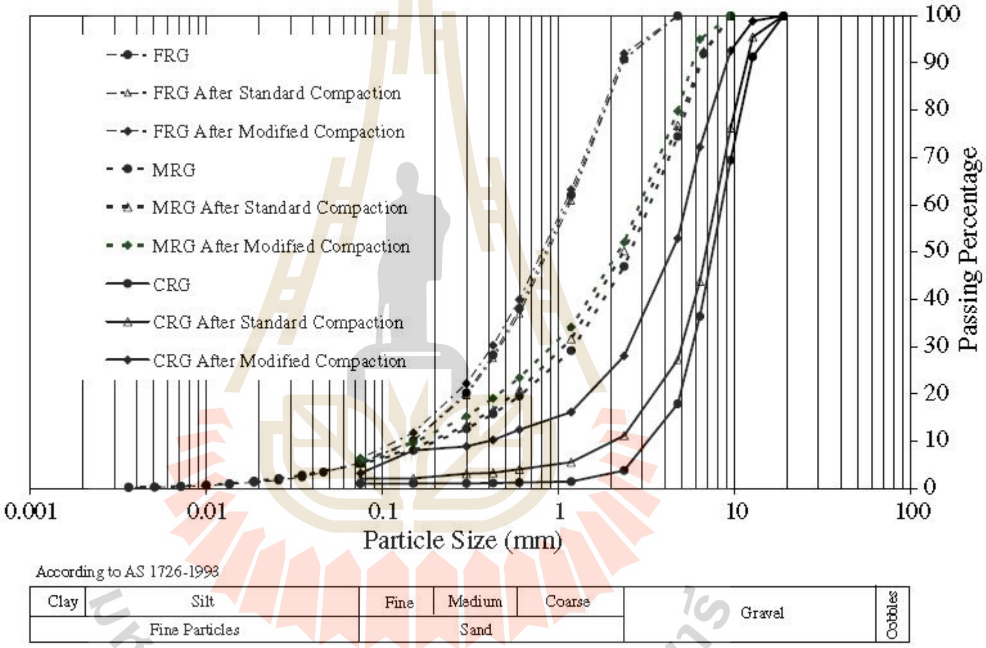


Upper bound
FRG Before compaction
FRG After compaction
FRG50/RCA50 Before compaction
FRG50/RCA50 After compaction
FRG40/RCA60 Before compaction
FRG40/RCA60 After compaction
FRG30/RCA70 Before compaction
FRG30/RCA70 After compaction
FRG20/RCA80 Before compaction
FRG20/RCA80 After compaction
FRG15/RCA85 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)
0.01
0.1
1
10
100

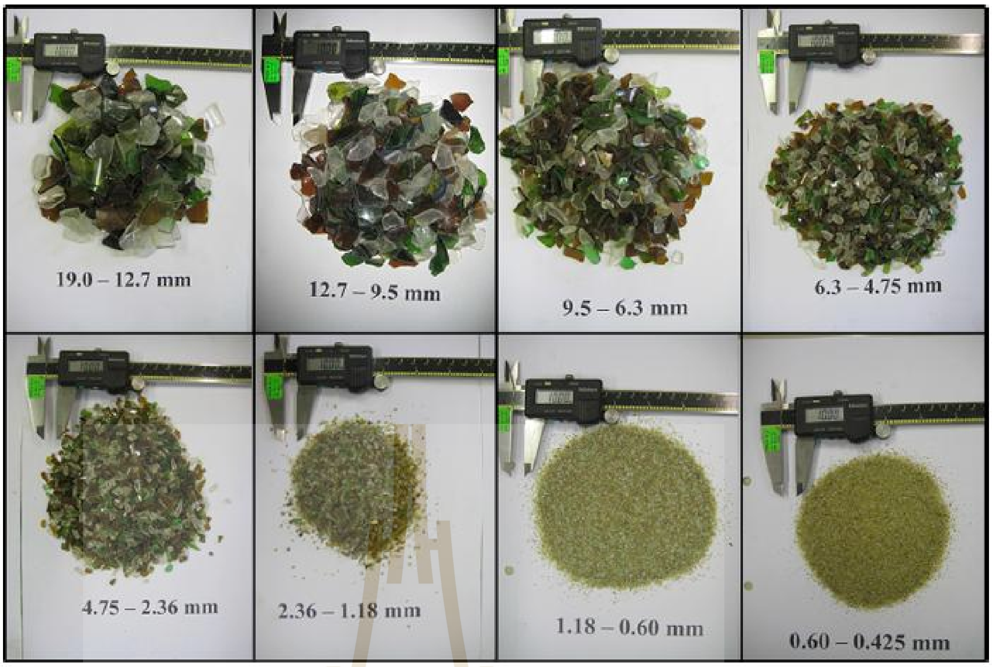

Upper bound
FRG Before compaction
FRG After compaction
FRG50/WR50 Before compaction
FRG50/WR50 After compaction
FRG40/WR60 Before compaction
FRG40/WR60 After compaction
FRG30/WR70 Before compaction
FRG30/WR70 After compaction
FRG20/WR80 Before compaction
FRG20/WR80 After compaction
FRG15/WR85 Before compaction
FRG15/WR85 After compaction
FRG10/WR90 Before compaction
FRG10/WR90 After compaction
WR Before compaction
WR After compaction
Lower bound
Total passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
100
Particle size (mm)


Dry density (Mg/m³)
Moisture content (%)
Zero-air-void curve (RCA)
Zero air void curve (FRG)
RCA100
FRG100
FRG10/RCA90
FRG15/RCA85
FRG20/RCA80
FRG30/RCA70
FRG40/RCA60
FRG50/RCA50
2.2
2.1
2.0
1.9
1.8
1.7
6.5 7.0 7.5 8.0 8.5 9.0 9.5 10.0 10.5 11.0 11.5 12.0 12.5 13.0 13.5 14.0

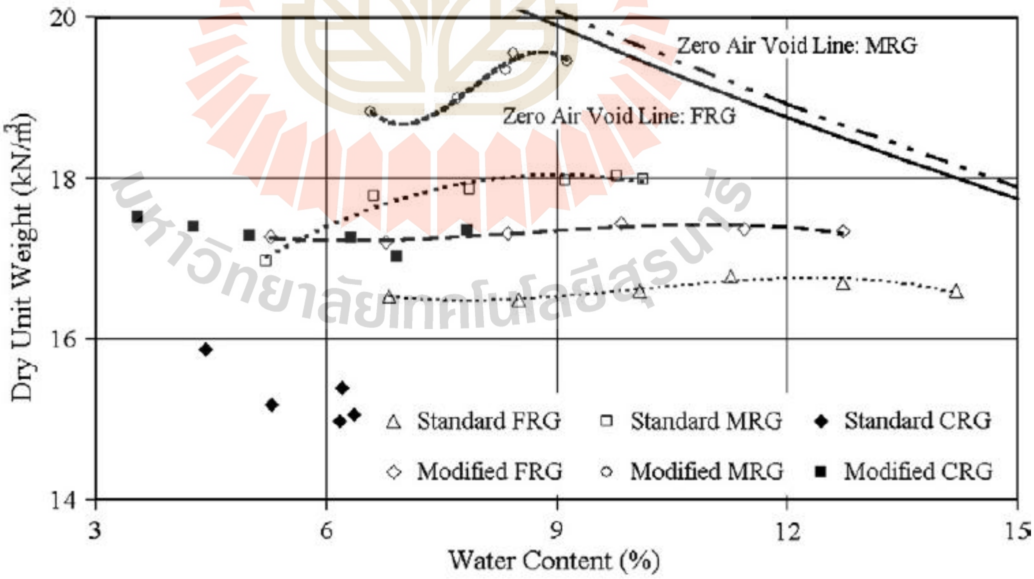

Dry density (Mg/m³)
Moisture content (%)
Zero-air-void curve (WR)
Zero-air-void curve (FRG)
WR100
FRG100
FRG10/WR90
FRG15/WR85
FRG20/WR80
FRG30/WR70
FRG40/WR60
FRG50/WR50
2.4
2.3
2.2
2.1
2.0
1.9
1.8
6.5 7.0 7.5 8.0 8.5 9.0 9.5 10.0 10.5



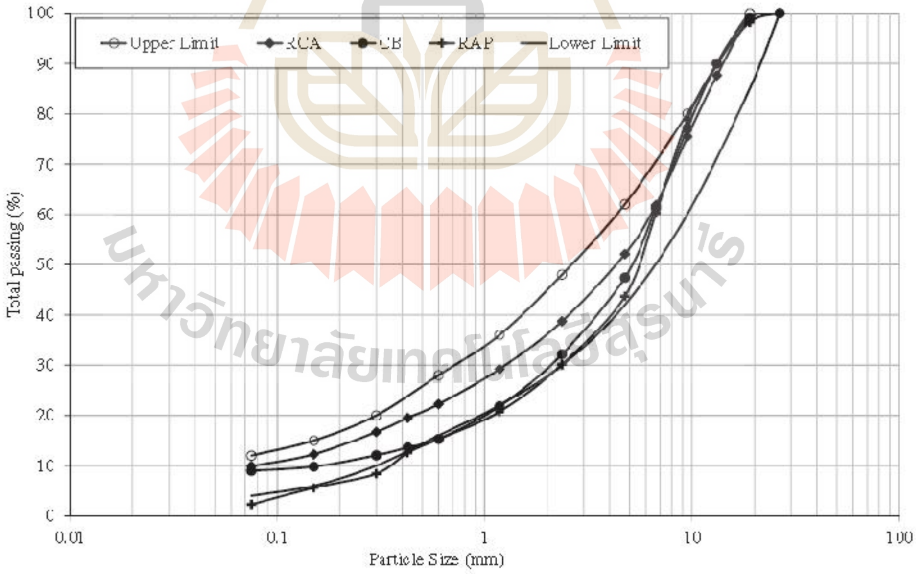
FRG
FRG After Standard Compaction
FRG After Modified Compaction
MRG
MRG After Standard Compaction
MRG After Modified Compaction
CRG
CRG After Standard Compaction
CRG After Modified Compaction
Passing Percentage
Particle Size (mm)
0.001
0.01
0.1
1
10
100
According to AS 1726-1993
Clay
Silt
Fine
Medium
Coarse
Gravel
Cobbles
Fine Particles
Sand



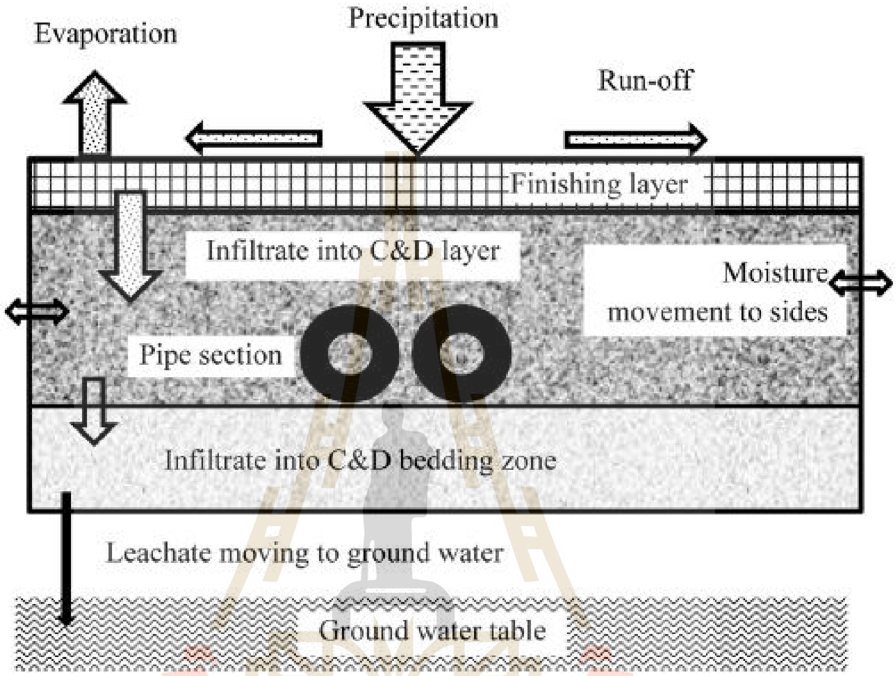
19.0 – 12.7 mm
12.7 – 9.5 mm
9.5 – 6.3 mm
6.3 – 4.75 mm
4.75 – 2.36 mm
2.36 – 1.18 mm
1.18 – 0.60 mm
0.60 – 0.425 mm

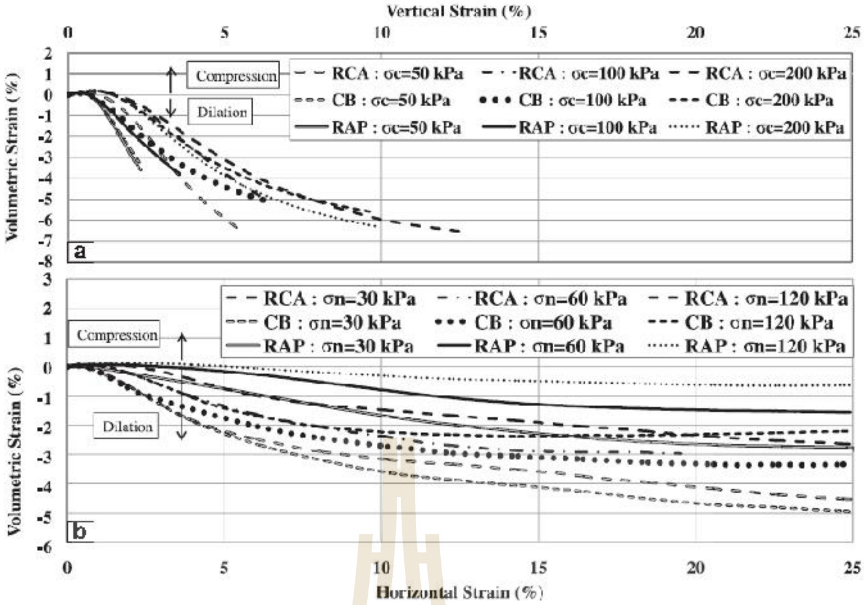
Zero Air Void Line: MRG
Zero Air Void Line: FRG
Dry Unit Weight (kN/m³)
Water Content (%)
Standard FRG
Standard MRG
Standard CRG
Modified FRG
Modified MRG
Modified CRG
20
18
16
14
3
6
9
12
15



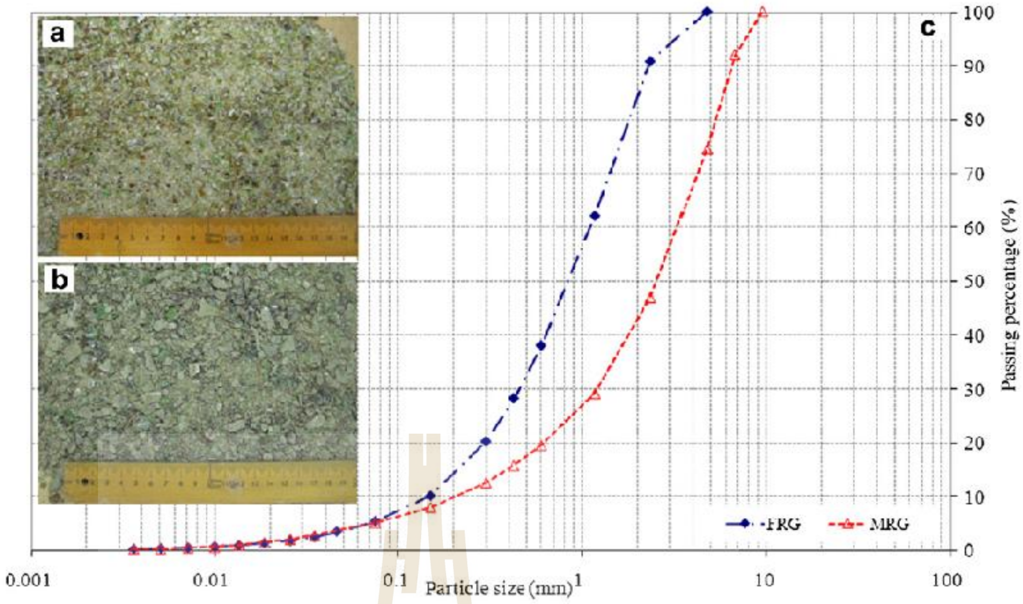
Upper Limit
RCA
CB
RAP
Lower Limit
Total passing (%)
Particle Size (mm)
0
10
20
30
40
50
60
70
80
90
100
0.01
0.1
1
10
100



Evaporation
Precipitation
Run-off
Finishing layer
Infiltrate into C&D layer
Moisture
movement to sides
Pipe section
Infiltrate into C&D bedding zone
Leachate moving to ground water
Ground water table



Vertical Strain (%)
Volumetric Strain (%)
Compression
Dilation
RCA : σc=50 kPa
RCA : σc=100 kPa
RCA : σc=200 kPa
CB : σc=50 kPa
CB : σc=100 kPa
CB : σc=200 kPa
RAP : σc=50 kPa
RAP : σc=100 kPa
RAP : σc=200 kPa
a
RCA : σn=30 kPa
RCA : σn=60 kPa
RCA : σn=120 kPa
CB : σn=30 kPa
CB : σn=60 kPa
CB : σn=120 kPa
RAP : σn=30 kPa
RAP : σn=60 kPa
RAP : σn=120 kPa
b
Horizontal Strain (%)




| Class | Landfill category | Leaching fluid |
|---|---|---|
| Class 1 | In situ-to be left undisturbed<br>At the site | Reagent water |
| Class 2 | Monofilled<br>• 2a:Putrescible material<br>• 2b:Non – putrescible material | <br>Acetate buffer pH 5.0<br>Reagent water |
| Class 3 | Co-disposed with<br>• 3a:Putrescible material<br>• 3b: Non – putrescible material | <br>Acetate buffer pH 5.0 or pH 2.9<br>Acetate buffer pH 5.0 or pH 2.9<br>And Tetraborate buffer pH 9.2<br>(i.e. two leaches) |
| Class 4 | Disposed of without confinement<br>e.g dispersed over land | Reagent water |

To address the environmental concerns of using recycled glass in road work applications, a comprehensive series of chemical and environmental tests including total and leachate concentration for a range of contaminant constituents including heavy metals and aromatic hydrocarbons were carried out.

**Table 2.2** US EPA drinking water and hazardous waste thresholds (Wartman et al., 2004).

| Contaminant | US EPA drinking water standard (mg/L) | Hazardous waste designation (mg/L) |
|---|---|---|
| Arsenic | 0.05 | 5.0 |
| Barium | 2.0 | 100.0 |
| Cadmium | 0.005 | 1.0 |
| Chromium | 0.1 | 5.0 |
| Lead | 0.015 | 5.0 |
| Mercury | 0.002 | 0.2 |
| Selenium | 0.05 | 1.0 |
| Silver | 0.05 | 5.0 |

Test results were compared with environmental protection authorities' requirements and indicated that no leaching hazard will be experienced during the service life of recycled glass in road work applications. Other possible environmental risks along with health and safety precautions and management suggestions have also been discussed.

Panyakapo and Panyakapo (2008) presented the utilization of thermosetting plastic as an admixture in the mix proportion of lightweight concrete. Since this type of plastic cannot be melted in the recycling process, its waste is expected to be more valuable by using as an admixture for the production of non-structural lightweight concrete. Experimental tests for the variation of mix proportion were carried out to determine the suitable proportion to achieve the required properties of lightweight concrete, which are: low dry density and acceptable compressive strength.

**Table 2.3** Mechanical and physical properties of melamine (Panyakapo and Panyakapo, 2008).

| Description | Properties |
|---|---|
| Specific gravity | 1.48 |
| Tensile strength (MPa) | 60 |
| Tensile elongation (%) | 0.79 |
| Notched izod impact (J/m) | 16.0 |
| Temperature resistance () | 300 |
| Water absorption (%) | 5.6 |

The mix design in this research is the proportion of plastic, sand, water cement ratio, aluminum powder, and lignite fly ash. The experimental results show that the plastic not only leads to a low dry density concrete, but also a low strength.



**Table 2.4** Comparison between plastic lightweight concrete and various standards (Panyakapo and Panyakapo.,2008).

| Description | Compressive strength ($N/mm^2$) | Dry density ($kg/cm^3$) |
|---|---|---|
| Plastic lightweight concrete (this study) cement:sand:fly ash:melamine = 1.0:0.8:0.3:0.9 | 4.14 | 1,395 |

| | | |
|---|---|---|
| Aerated lightweight concrete (TIS 1505-1998) Class 2 | 2.5 | 300-500 |
| Aerated lightweight concrete (Quality Construction Products, 2001) | 3.0-8.0 | 500-700 |
| Clay brick (commercial) | 2.0-3.0 | 1800 |

It was found that the ratio of cement, sand, fly ash, and plastic equal to 1.0:0.8:0.3:0.9 is an appropriate mix proportion. The results of compressive strength and dry density are 4.14 N/mm$^2$ and 1,395 kg/m$^3$, respectively. This type of concrete meets most of the requirements for nonload-bearing lightweight concrete according to ASTM C129 Type II standard.

## 2.5 Summary of previous researchers

Previous research studies showed the possibility of use of wastes in geotechnical engineering applications, which can reduce the environmental impact and the construction cost. With the continuous increase in amount of research MD and its lows density, MD can be used to make lightweight concrete. This thesis attempts to study the possibility of using the melamine debris to develop lightweight pavement base and subbase, which is significant in term of engineering and environmental perspectives.

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# CHAPTER III

# IMPROVEMENT OF MARGINAL LATERITIC SOIL USING MELAMINE DEBRIS REPLACEMENT FOR SUSTAINABLE ENGINEERING FILL MATERIALS

## 3.1 Introduction

Quality pavement subbase/base and engineering fill materials are becoming increasingly scarce to source for road infrastructure projects. When no suitable materials are available at a construction site, these materials need to be hauled from distant sources, which is uneconomical and at a cost to the environment. Therefore, modification of soils on site is an attractive, economical and environmental friendly option to improve their mechanical properties (Horpibulsuk et al., 2006, 2012 and 2013 and Du et al., 2013 and 2014). The most common soil improvement technique is to compact the locally available soil blended with quality materials. Compaction is simple, practical and economical technique to improve the mechanical properties of soils. Compaction is the process of increasing the soil unit weight by forcing the soil particles into a tighter state with less air void, by the addition of either static or dynamic force (Horpibulsuk et al., 2008 and 2009 and Bo et al., 2014).

The stockpile of waste materials generated by the everyday activities of a growing population has become a persistent problem, which is furthermore exacerbated by the lack of available technologies to adequately treat or dispose of these waste materials (Ribeiro de Rezende et al., 2014). Several authors have researched on the utilization of various recycled materials in geotechnical and pavement applications. The usage of recycled materials to stabilize marginal soils has significant economical and environmental impacts and has been recently performed (Arulrajah et al., 2014a and 2014b; Kampala and Horpibulsuk, 2013; Kampala et al., 2013 and Phetchuey et al., 2014). This includes 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 used with geotextile 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) and crushed brick as supplementary material in bound pavement (Disfani et al., 2014). The utilization of these recycled materials has a significant impact on the sustainability of our scarce natural resources and the reduction of construction and industrial wastes.

Industrial wastes resulting from the rapid development in developed and developing countries is the prime factor responsible for environmental degradation. The recycling of industrial waste materials has consolidated its presence as an efficient mechanism to minimize the problems arising from the wastes generated by anthropic activities. (Ribeiro de Rezende et al., 2014).

Melamine debris (MD) is a waste material resulting from plate and cup manufacture. This MD cannot be reformed or reused for manufacturing plates and cups (Siwadamrongpong, et al. 2012). It was reported by Srithai Superware Public Co., Ltd, a largest melamine tableware company in Thailand, that the company releases 400 tons of MD annually. Presently, this MD is disposed by burning at a very high temperature, which damages the air environment and is furthermore costly. The sustainable usage of MD in civil engineering applications will provide lower a carbon footprint and result in positive social and economical impacts for governments, industry and consumers.

The usage of MD in marginal soil improvement for pavement application is innovative and of interest to the industrial sectors and national road authorities, particularly as road construction requires a large volume of quality material. This paper investigates physical and geotechnical properties of marginal lateritic soil blended with MD at various replacement ratios to ascertain it as an engineering fill material. This research will enable MD traditionally disposed to landfill, to be used in a sustainable manner as a non-plastic replacement material for marginal soil (high fine content) improvement. The outcome of this research in MD is significant in term of engineering, economical and environmental perspectives for developed and developing countries.

## 3.2 Materials and methods

Marginal lateritic soil samples were collected from a borrow pit in Maung district, Sakonnakhon province, Thailand (**Figure 3.1a**) at approximately 1.5 meter depth. The lateritic soil is composed of 21.7% fine-grained particles and 78.3% coarse-grained particles in which 25.6% is gravel and 31% is sand. The specific gravity of coarse-grained particles is 2.67 and the liquid and plastic limits are 40.7% and 20.9%, respectively. According to the Unified Soil Classification System (USCS), the lateritic soil is classified as clayey sand (SC). The grain size distribution curve is shown in **Figure 3.2** and basic properties are summarized in **Table 3.1**. According to the local road authority specifications for subbase material (DH-S205/2532) and for engineering fill material (DH-S208/2532), this lateritic soil does not meet the standards, and will require blending with a higher quality material if it is to be considered as a pavement subbase or fill material.

Melamine Debris (MD) was obtained from Srithai Superware Public Co., Ltd, Nakhon Rachasima, Thailand. MD particles are shown in **Figure 3.1b**. The grain size distribution of MD (**Figure 3.2**) shows that MD is composed of 0.9% fine-grained particles and 99.1% coarse-grained particles. It is a non-plastic material and is classified as poorly graded sand (SP) based on USCS. The bulk specific gravities of fine-grained and coarse-grained particles are 1.45 and 1.38, respectively.

The laboratory evaluation program on marginal lateritic soil/MD blends included specific gravity, water absorption, Atterberg limit, particle-size distribution, modified Proctor compaction, Los Angeles (LA) abrasion, and 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). The lateritic soil : MD ratios studied were 100:0, 50:50, 60:40, 70:30, 80:20, 90:10 and 0:100. **Figure 3.1c** shows the particles of lateritic soil/MD blend at 50:50 ratio.

The specific gravity and water absorption tests were performed in accordance with AASHTO T 85-70 and AASHTO T 84, respectively. 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. The 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.

Modified compaction effort was used to determine the maximum dry density (MDD) and optimum moisture content (OMC) of the lateritic soil/MD blends. The modified compaction tests were conducted by following the AASHTO T 180. 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).

**Table 3.1** Geotechnical properties of marginal lateritic soil, MD and lateritic soil/MD blends before modified compaction test.

| Sample Description | MD | Lateritic Soil : MD | | | | | Lateritic Soil | Remark |
|---|---|---|---|---|---|---|---|---|
| | | 50:50 | 60:40 | 70:30 | 80:20 | 90:10 | | |
| Bulk specific gravity Coarse-grained | 1.38 | 2.01 | 2.08 | 2.21 | 2.20 | 2.19 | 2.67 | AASHTO T85-70 |
| Bulk specific gravity Fine-grained | 1.45 | 1.98 | 2.03 | 2.17 | 2.02 | 2.29 | 3.03 | AASHTO 84 |
| Apparent specific gravity Coarse-grained | 1.53 | 2.32 | 2.41 | 2.57 | 2.57 | 2.54 | 3.18 | AASHTO T85-70 |
| Apparent specific gravity Fine-grained | 1.69 | 2.44 | 2.51 | 2.73 | 2.53 | 2.86 | 3.47 | AASHTO 84 |
| Water absorption Coarse-grained | 6.99 | 6.64 | 6.61 | 6.40 | 6.58 | 6.34 | 5.95 | AASHTO T85-70 |
| Water absorption Fine- grained (%) | 9.72 | 9.59 | 9.32 | 9.56 | 9.93 | 8.65 | 4.19 | AASHTO 84 |
| LA abrasion value (%) | 11.3 | 41.1 | 43.3 | 47.6 | 50.4 | 51.4 | 58.1 | ASTM C131 ,C535 |
| LL. (%) | - | 37.8 | 38.4 | 38.9 | 39.8 | 39.9 | 40.7 | AASHTO T90 |
| PL. (%) | - | 26.7 | 25.8 | 23.8 | 23.2 | 22.9 | 20.9 | AASHTO T90 |
| PI. (%) | - | 11.1 | 12.6 | 15.1 | 16.6 | 17.0 | 19.8 | |
| $D_{10}$ (mm) | 0.90 | - | - | - | - | - | - | |
| $D_{30}$ (mm) | 2.00 | 1.25 | 2.00 | 0.85 | 1.50 | 1.20 | 1.80 | |
| $D_{50}$ (mm) | 3.00 | 3.50 | 4.00 | 3.50 | 3.80 | 3.50 | 4.50 | |
| $D_{60}$ (mm) | 3.80 | 4.75 | 5.20 | 5.00 | 5.30 | 4.90 | 5.50 | |
| $C_u$ | 4.22 | - | - | - | - | - | - | |
| $C_C$ | 1.17 | - | - | - | - | - | - | |
| Gravel size content(%) | 24.6 | 41.3 | 41.8 | 41.9 | 44.2 | 40.9 | 47.3 | Retained #4 |
| Sand size content(%) | 74.5 | 41.8 | 36.8 | 36.9 | 35.9 | 38.9 | 31.0 | Passed#4-Retain#200 |
| Fines size content(%) | 0.9 | 16.9 | 18.4 | 21.2 | 19.9 | 20.2 | 21.7 | Passed#200 |
| Classification-USCS | SP | SM | SM | SM | SC | SC | SC | |

above the upper boundary and MD particles finer than 1.05 mm ($D_{20}$) are below the lower boundary.

**Table 3.2** Geotechnical properties of marginal lateritic soil, MD and lateritic soil/MD blends after modified compaction test.

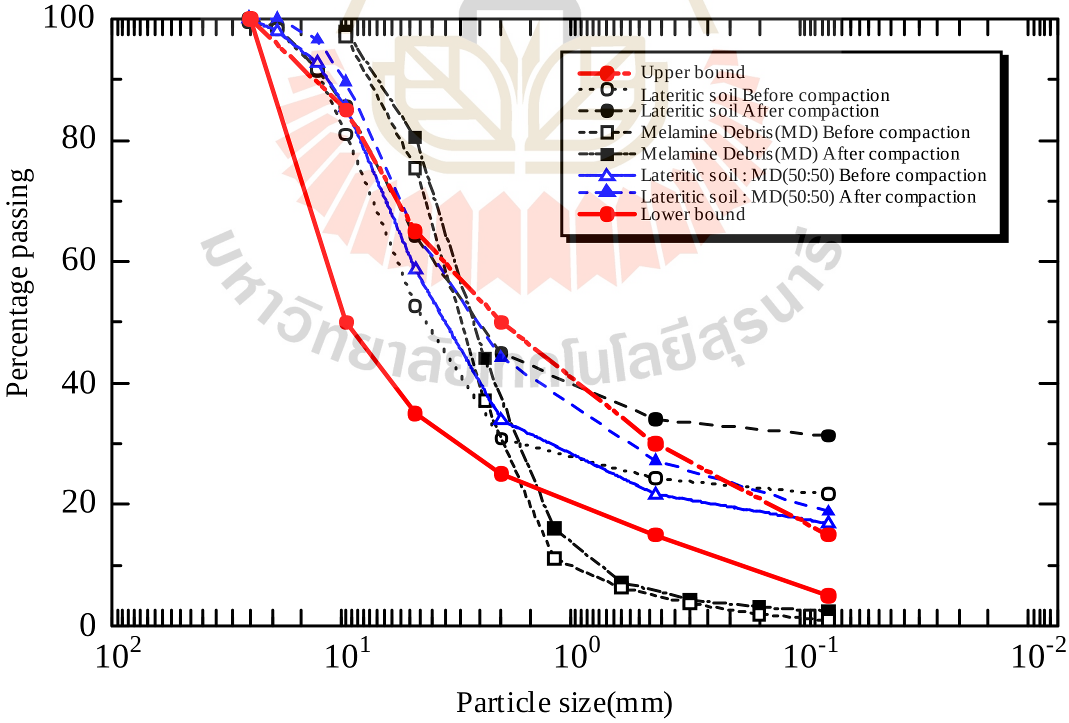
| Sample Description | MD | Lateritic Soil : MD | | | | | Lateritic Soil | Remark |
|---|---|---|---|---|---|---|---|---|
| | | 50:50 | 60:40 | 70:30 | 80:20 | 90:10 | | |
| Compaction (Modified):Max Dry Density(KN/m$^3$) | 8.2 | 16.0 | 17.3 | 18.2 | 18.9 | 19.4 | 21.6 | AASHTO T180 |
| Compaction (Modified):OMC (%) | 10.0 | 14.0 | 12.5 | 12.0 | 9.0 | 11.0 | 7.60 | AASHTO T180 |
| California Bearing Ratio (Soaked 4 days) (%) | - | 21.0 | 20.0 | 16.0 | 15.5 | 13.5 | 9.3 | AASHTO T193 |
| Swell (Soaked 4 days) (%) | - | 0.31 | 0.55 | 0.86 | 1.60 | 3.05 | 6.40 | AASHTO T193 |
| LL. (%) | - | 38.1 | 38.8 | 40.7 | 43.0 | 44.9 | 45.6 | AASHTO T90 |
| PL. (%) | - | 27.1 | 26.4 | 24.9 | 25.3 | 25.9 | 24.6 | AASHTO T90 |
| PI. (%) | - | 11.0 | 12.4 | 15.8 | 17.7 | 19.0 | 21.0 | |
| $D_{10}$ (mm) | 0.8 | - | - | - | - | - | - | |
| $D_{30}$ (mm) | 1.75 | 0.65 | 0.85 | 0.60 | 0.65 | 0.55 | - | |
| $D_{50}$ (mm) | 2.60 | 2.75 | 3.25 | 2.75 | 3.00 | 2.90 | 2.50 | |
| $D_{60}$ (mm) | 3.20 | 4.00 | 4.50 | 4.00 | 4.50 | 4.20 | 4.00 | |
| $C_u$ | 4.0 | - | - | - | - | - | - | |
| $C_C$ | 1.2 | - | - | - | - | - | - | |
| Gravel size content(%) | 19.5 | 35.1 | 37.7 | 34.4 | 38.6 | 37.3 | 35.8 | Retained #4 |
| Sand size content(%) | 78.1 | 46.2 | 41.9 | 41.9 | 36.4 | 37.5 | 32.9 | Passed#4-Retain#200 |
| Fines size content(%) | 2.4 | 18.7 | 20.4 | 23.7 | 25.0 | 25.2 | 31.3 | Passed#200 |
| Classification-USCS | SP | SM | SM | SC | SC | SC | SC | |

**Figures 3.2** to **3.6** show that MD replacement reduces the fine contents of lateritic soil. Almost all particle sizes of the lateritic soil/MD blend at 50% MD replacement are within the boundaries for base and subbase materials except the fine content being slightly higher than upper boundary (15%). This blend is possibly used as subbase material if more MD replacement (>50%) is used. Even though the gradation of

all tested blends does not meet this specification, the fine content is reduced significantly with increasing MD replacement ratio and can be possibly used as the selected material. Due to the reduction in fine content, the liquid limit (LL) and plasticity index (PI) reduce; i.e., LL is 39.9%, 39.8%, 38.9%, 38.4% and 7.8% and PI is 17.0, 16.6, 15.1, 12.6 and 11.1 for MD replacement ratios of 10%, 20%, 30%, 40% and 50%, respectively. LL and PI of these blends meet the consistency limits specified for selected material (LL < 40% and PI < 20%). Consequently, the lateritic soil/MD blends approach to silty material with increasing MD replacement ratio; i.e., they are classified as SM, SM, SM, SC and SC for MD replacement ratios of 10%, 20%, 30%, 40% and 50%, respectively while the lateritic soil is classified is SC.

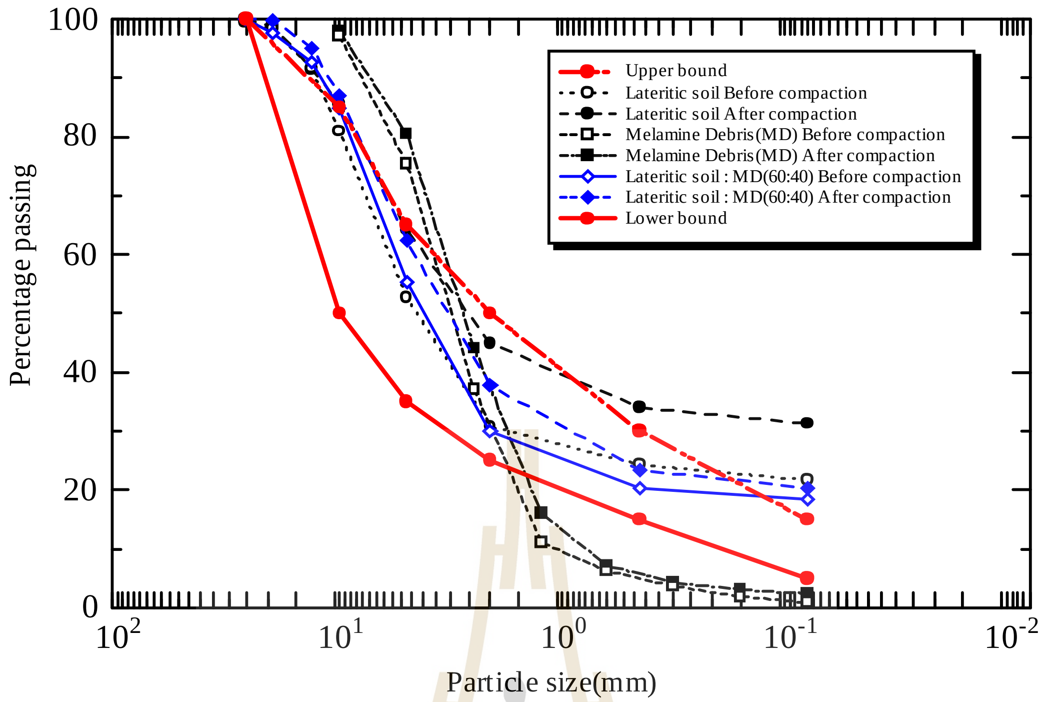
Besides the physical properties, the durability of the lateritic soil particles is improved by the MD replacement. The MD has a relatively low LA abrasion of 11.3% compared to the lateritic soil whose LA is 58.1%. Therefore, the MD replacement improves the LA abrasion of the lateritic soil by reducing the LA abrasion value for the blends. The LA abrasion of lateritic soil decreases from 58.1% (for 0% MD replacement) to 41.1% (for 50% MD replacement). Even without the MD replacement, this lateritic soil is considered as durable for subbase and selected materials based on LA abrasion requirement of < 60% (DH-S, 1996).

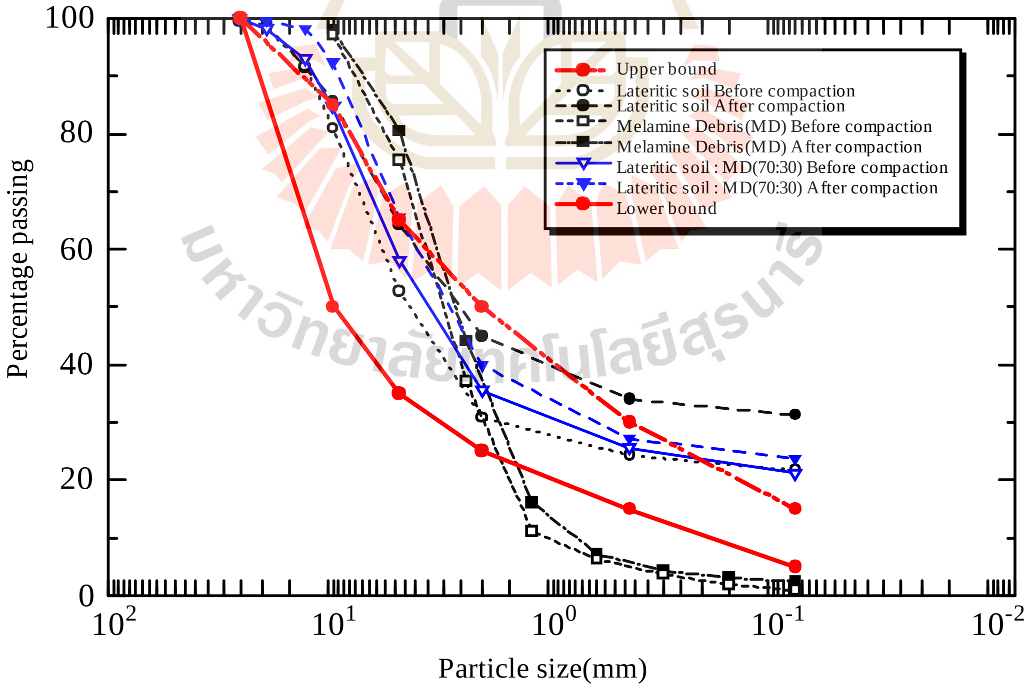
It is now to examine the mechanical properties of compacted blends as an engineering fill material. The modified compaction test results (**Table 3.2** and **Figure 3.7**) show that the blends at various MD replacement ratios exhibit bell-shaped compaction pattern, typical of traditional geo-materials (Horpibuksuk et al., 2008 and 2009). The maximum dry density (MDD) of the MD is relatively low (8.2 kN/m$^3$)

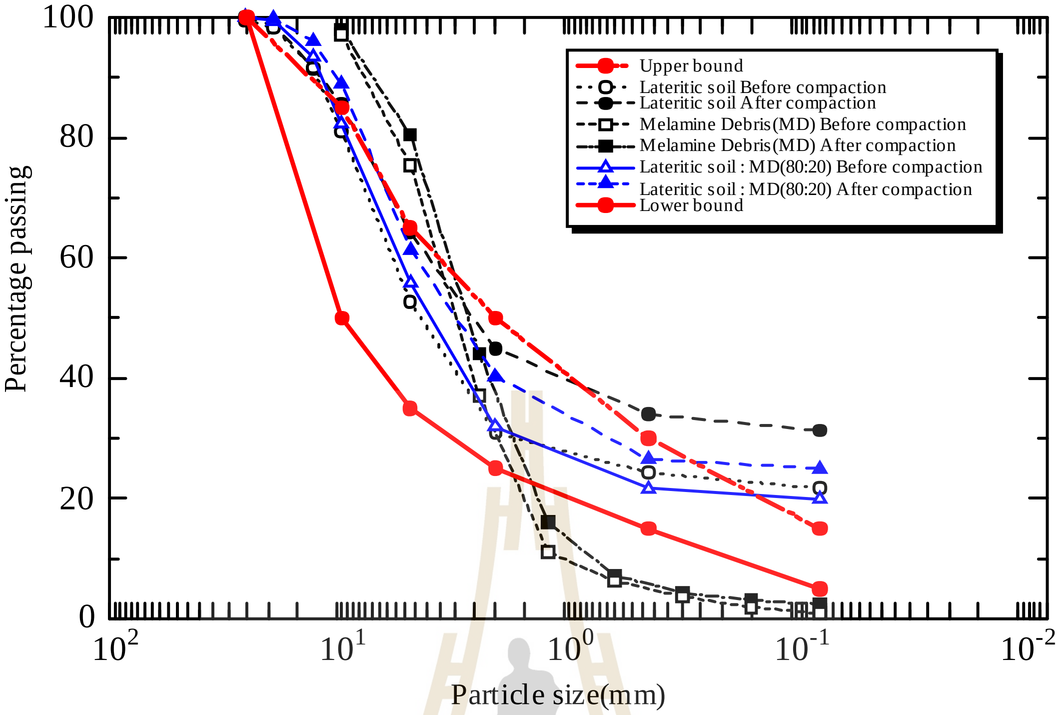


100
80
60
40
20
0
Percentage passing
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
Particle size(mm)
Upper bound
Lateritic soil Before compaction
Lateritic soil After compaction
Melamine Debris(MD) Before compaction
Melamine Debris(MD) After compaction
Lateritic soil : MD(50:50) Before compaction
Lateritic soil : MD(50:50) After compaction
Lower bound

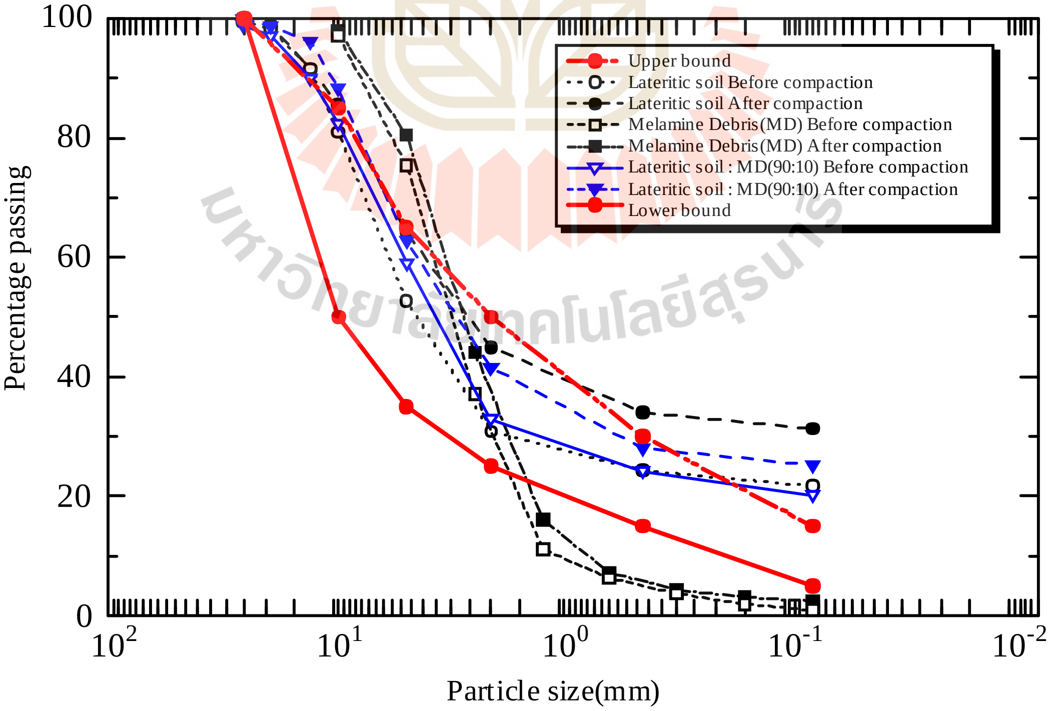
The MD replacement also has the advantage with particle breakage of the blends due to compaction as evident from **Figures 3.2-3.6**. The lateritic soil particles are broken down significantly, particularly for particles smaller than 10 mm while the MD particle breakage is insignificant. By comparing **Tables 3.1** and **3.2**, it is evident that after compaction, the gravel-sized and sand-sized particles of lateritic soil decrease while the silt-sized and clay-sized particles increase; 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. The coarse (gravel and sand) content of MD decreases from 99.1% to 97.6% while the clay content increases from 0.9% to 2.4% after compaction. The change in coarse content of MD is minimal because the decrease in gravel-sized particles is associated with the increase in sand-sized particles (**Table 3.2**). As such, the MD replacement possibly prevents the breakage of the coarse aggregate and hence the minimal reduction of the fine content as noted by the small increase in fine content with increasing MD replacement ratio.


Upper bound
Lateritic soil Before compaction
Lateritic soil After compaction
Melamine Debris(MD) Before compaction
Melamine Debris(MD) After compaction
Lateritic soil : MD(60:40) Before compaction
Lateritic soil : MD(60:40) After compaction
Lower bound
Percentage passing
Particle size(mm)
100
80
60
40
20
0
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$


Upper bound
Lateritic soil Before compaction
Lateritic soil After compaction
Melamine Debris(MD) Before compaction
Melamine Debris(MD) After compaction
Lateritic soil : MD(70:30) Before compaction
Lateritic soil : MD(70:30) After compaction
Lower bound
Percentage passing
Particle size(mm)
100
80
60
40
20
0
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$



Upper bound
Lateritic soil Before compaction
Lateritic soil After compaction
Melamine Debris(MD) Before compaction
Melamine Debris(MD) After compaction
Lateritic soil : MD(80:20) Before compaction
Lateritic soil : MD(80:20) After compaction
Lower bound
Percentage passing
Particle size(mm)
0
20
40
60
80
100
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$

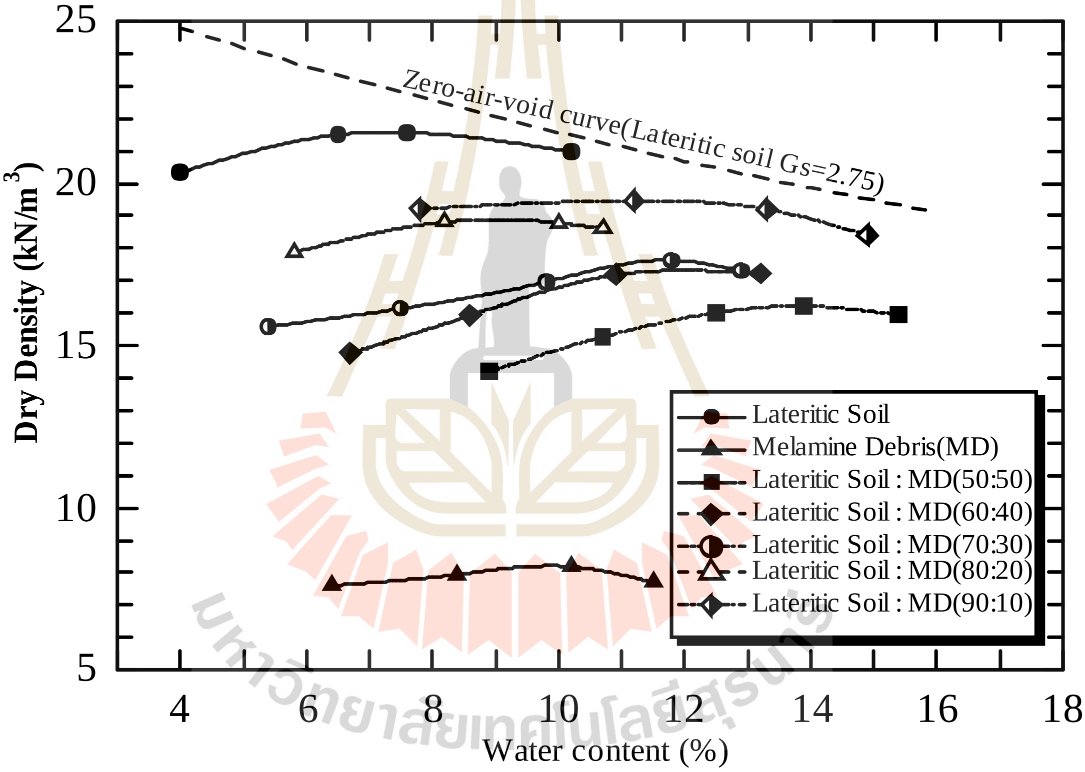



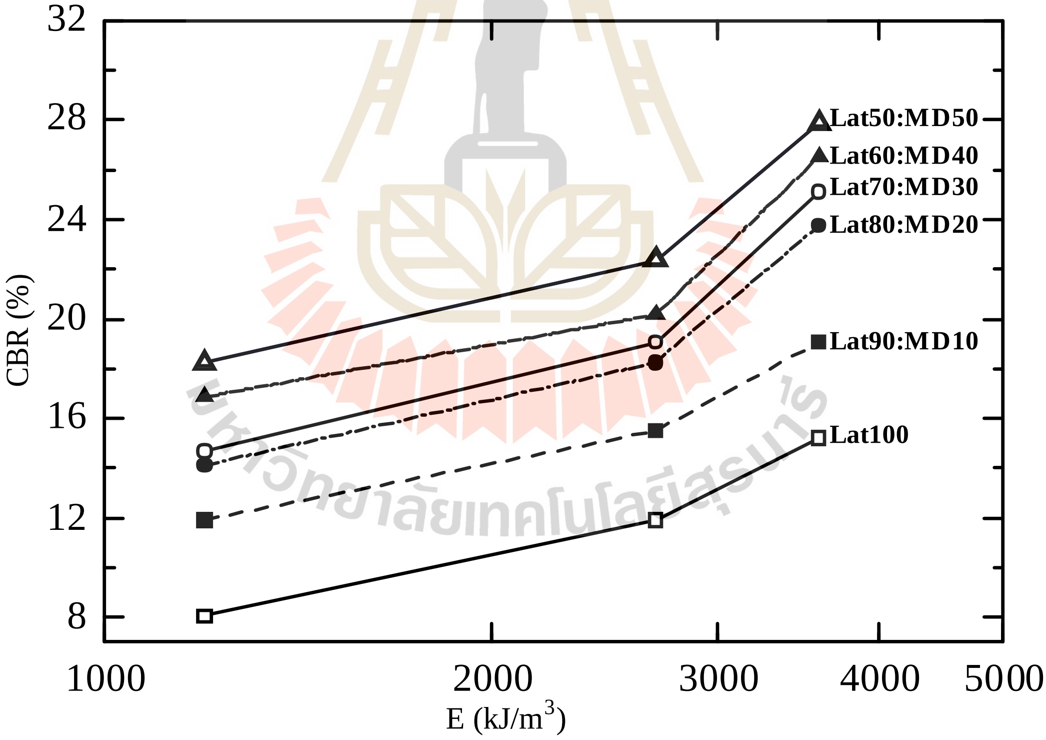
Upper bound
Lateritic soil Before compaction
Lateritic soil After compaction
Melamine Debris(MD) Before compaction
Melamine Debris(MD) After compaction
Lateritic soil : MD(90:10) Before compaction
Lateritic soil : MD(90:10) After compaction
Lower bound
Percentage passing
Particle size(mm)
0
20
40
60
80
100
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$

The difference in fine content of the blends before and after compaction is 5.0%, 5.1%, 2.5%, 2.0% and 1.8% for MD replacement ratios of 10%, 20%, 30%, 40% and 50%, respectively. This implies that the higher MD replacement results in lesser particle breakage. The soil classification of the blends before and after compaction remains the same for all MD replacement except 30% MD replacement. At 30% MD replacement, the soil classification changes from SM to SC, which indicates that this replacement ratio is threshold limit for this replacement method.

The particle breakage leads to the increase in liquid limit and plastic limit of lateritic soil. Without the MD replacement, LL increases from 40.7% to 45.6% and PI from 19.8% to 21.0% after compaction. Whereas the change in LL and PI after compaction is insignificant particularly for 50% MD replacement. Since the geotechnical properties of compacted materials is governed by the gradation and physical properties of after-compaction properties, the more particle breakage results in the poorer geotechnical properties. In other words, the MD replacement prevents the particle breakage and hence the improvement of mechanical properties. Two mechanical properties required for subbase and fill materials are CBR and swelling.

Generally, bearing capacity or CBR and swelling of the compacted materials are controlled by fine content. The higher fine 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. Since the higher MD replacement results in the lower fine content and water holding capacity, the higher CBR. The CBR values at modified Proctor energy of each blend are 13.5%, 15.5%, 16.0%, 20.0% and 21.0% for 10%, 20%, 30%, 40% and 50% replacement.


Zero-air-void curve(Lateritic soil Gs=2.75)
Dry Density (kN/m^3)
Water content (%)
25
20
15
10
5
4
6
8
10
12
14
16
18
Lateritic Soil
Melamine Debris(MD)
Lateritic Soil : MD(50:50)
Lateritic Soil : MD(60:40)
Lateritic Soil : MD(70:30)
Lateritic Soil : MD(80:20)
Lateritic Soil : MD(90:10)



32
28
24
20
16
12
8
CBR (%)
1000
2000
3000
4000
5000
E (kJ/m$^3$)
Lat50:MD50
Lat60:MD40
Lat70:MD30
Lat80:MD20
Lat90:MD10
Lat100

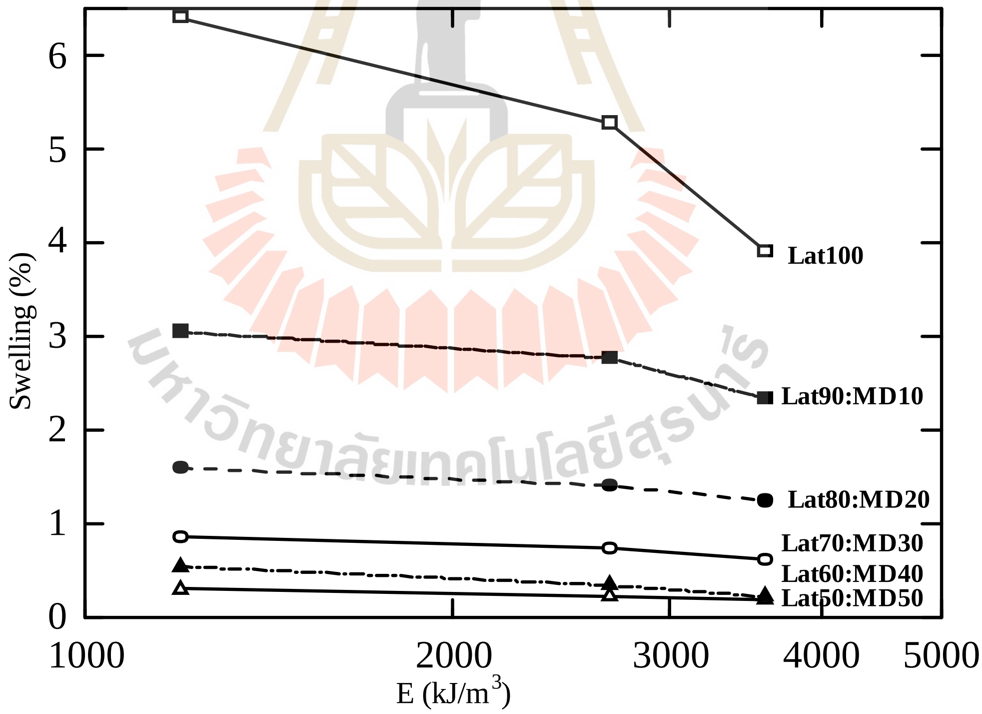
**Figure 3.9** shows the swelling versus logarithm of *E* relationship for various MD replacement ratios. Similar to the soaked CBR versus logarithm of *E* relationship, the *E* = 2681 kJ/m$^3$ is regarded as threshold limit separating the first and second slopes of swelling versus logarithm of *E* relationship for lateritic soil. Without MD replacement, *E* can reduce the swelling, especially when *E* > 2681 kJ/m$^3$ as seen that the second slope is remarkably lower than the first slope. Besides *E*, MD replacement significantly reduces the swelling. By replacing lateritic soil with MD, the swelling significantly reduces; i.e., the swelling of lateritic soil reduces more than twice when only 10% MD is replaced. The first and second slopes of the blends are essentially the same and can be represented by a gentle linear function when MD replacement is greater 20%. In other words, the swelling of the blends is significantly reduced even at a small *E* level unlike the marginal lateritic soil (without MD), which requires high *E* level to increase attractive forces among soil particles.

Based on an analysis of soaked CBR and swelling test results, it is practical to relate the soaked CBR and swelling of blends at various compaction energies in term of MD replacement. **Figures 3.8** and **3.9** shows that the improvement rate of CBR is significantly dependent upon *E*. *E* = 2681 kJ/m$^3$ is found to be the threshold limit while the improvement rate of swelling is marginally dependent upon *E*. As such, the predictive equations for soaked CBR and swelling in term of MD replacement ratio are presented as follows:

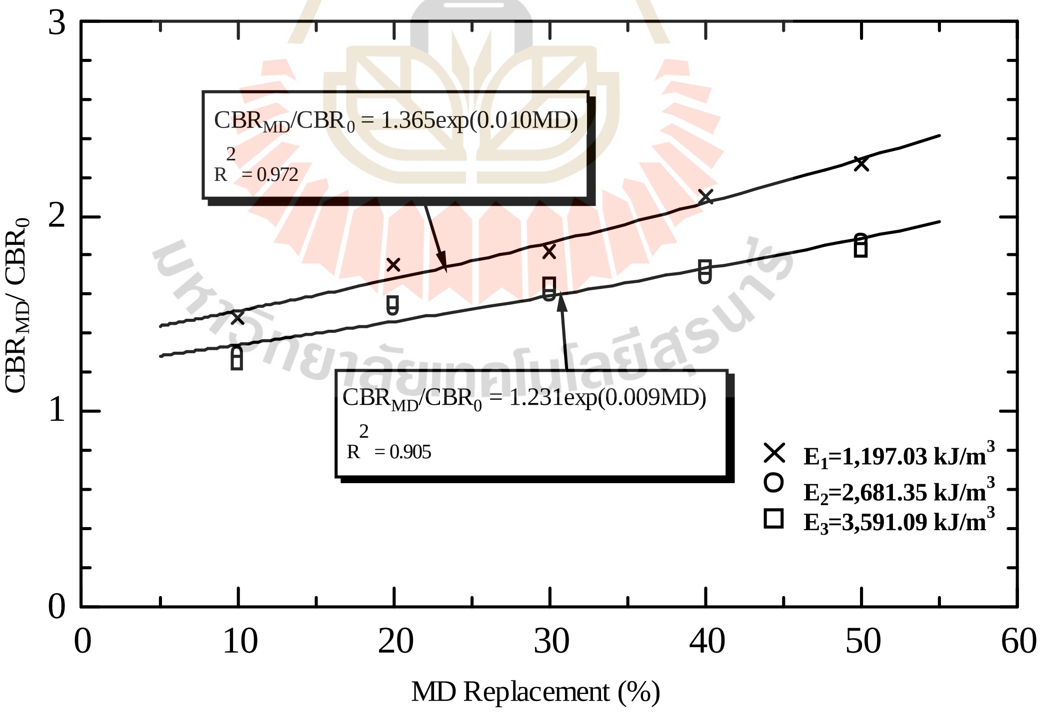
$$\frac{CBR_{MD}}{CBR_0} = 1.365\exp(0.010MD) \quad \text{for} \quad 1197\ \text{kJ/m}^3 < E < 2681\ \text{kJ/m}^3 \tag{3.1}$$

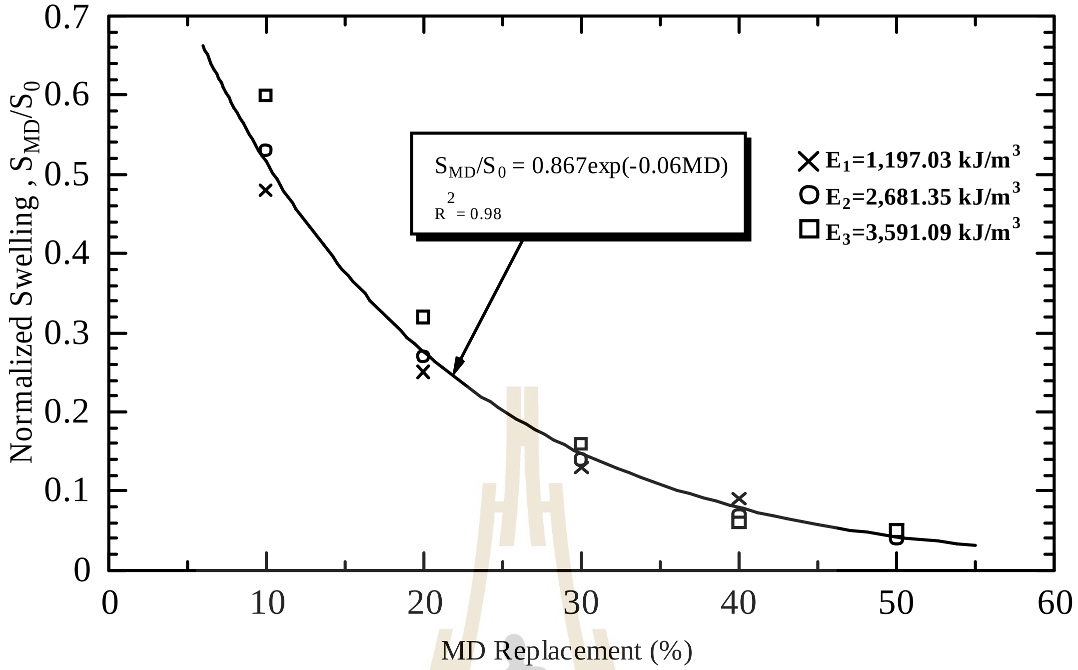
$$\frac{CBR_{MD}}{CBR_0} = 1.231\exp(0.009MD) \quad \text{for} \quad 2681\ \text{kJ/m}^3 < E < 3591\ \text{kJ/m}^3 \tag{3.2}$$

$$\frac{S_{MD}}{S_0} = 10.867 \exp(-0.06MD)$$



| Sample Description | Subbase Material (DH-S205/2532) | Engineering Fill Material (DH-S208/2532) | MD | Lateritic Soil : MD 50:50 | 60:40 | 70:30 | 80:20 | 90:10 | Lateritic Soil |
|---|---|---|---|---|---|---|---|---|---|
| LA abrasion value (%) | ≤ 60 | ≤ 60 | 11.3 | 41.1 | 43.3 | 47.6 | 50.4 | 51.4 | 58.1 |
| California Bearing Ratio (%) | ≥ 25 | ≥10 | - | 21.0 | 20.0 | 16.0 | 15.5 | 13.5 | 9.3* |
| Swell (%) | ≤ 4 | ≤ 3 | - | 0.31 | 0.55 | 0.86 | 1.60 | 3.05* | 6.40* |
| LL (%) | ≤ 35 | ≤ 40 | - | 37.8 | 38.4 | 38.9 | 39.8 | 39.9 | 40.7* |
| PI (%) | ≤ 11 | ≤ 20 | - | 11.1 | 12.6 | 15.1 | 16.6 | 17.0 | 19.8 |
| Remark | | | - | Meet to Selection Material | | | | | *Not meet. |





Normalized Swelling , $S_{MD}/S_0$
MD Replacement (%)
$S_{MD}/S_0$ = 0.867exp(-0.06MD)
$R^2$ = 0.98
$E_1$=1,197.03 kJ/$m^3$
$E_2$=2,681.35 kJ/$m^3$
$E_3$=3,591.09 kJ/$m^3$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
10
20
30
40
50
60

## 3.4 Conclusions

The marginal lateritic soil improvement by Melamine Debris (MD) replacement is found to be a sustainable engineering fill material based on this research. The laboratory evaluation of the lateritic soil/MD blends at different MD replacement ratios includes physical properties (particle size distribution, Atterberg limits, compaction, LA abrasion tests) and mechanical properties (soaked CBR and swelling tests). The conclusions can be drawn as follows:

1. The MD can improve both physical and mechanical properties of marginal lateritic soil. The MD is a non-plastic and coarse-grained material. Hence, the liquid limit and plasticity index of lateritic soil reduce with increasing MD replacement. With low LA abrasion (of 11.3%) of MD, the MD replacement enhances the durability against traffic load to the marginal lateritic soil.

2. Due to the low specific gravity of MD, the unit weight of blends decreases with increasing MD replacement. With this lower unit weight and better geotechnical properties, the lateritic soil/MD blends provide lower overburden of the pavement structure on foundation and higher stability than the conventional pavement materials.

3. The compaction breaks down the coarse grains of the lateritic soil and hence the increase in fine content. With higher abrasion of MA, the MD replacement improves the particle breakage due to compaction, resulting in lower fine content. This lower fine content of compacted blends with higher MD replacement ratios increases soaked CBR and decreases swelling.

4. The compaction energy, $E$ affects the rate of soaked CBR development with MD replacement ratio. The development rate at $E$ < 2681 kJ/m$^3$ is essentially the same

even with different MD replacement ratios. The higher rate of soaked CBR development is noticed when $E$ > 2681 kJ/m$^3$. As such, two predictive equations for soaked CBR in term of MD replacement ratio are proposed for $E$ < 2681 kJ/m$^3$ and $E$ > 2681 kJ/m$^3$, respectively.

5. Even though the water absorption of blends increases with increasing MD replacement, the swelling decreases with increasing MD replacement ratio because MD is non-plastic material. The rate of swelling reduction with MD replacement is essentially the same for all $E$ values tested. Consequently, a unique predictive equation for swelling in term of MD replacement is proposed for various $E$ values. The predictive equations for soaked CBR and swelling proposed are useful for geotechnical and pavement practitioners. The soaked CBR and swelling of blends at various MD replacement ratios and $E$ values can be predicted once the soaked CBR and swelling of lateritic soil (without MD) are known. The formulation of the proposed equations is based on sound principle and can be extended to other types of marginal soils.

6. The MD replacement can improve the geotechnical property requirement for engineering fill material according to national local authority. The MD traditionally destined for landfill can be used as a replacement material to stabilize lateritic soil for developing the sustainable fill material. With 20% MD replacement, the physical and mechanical properties of blends meet the requirement. The 50% MD replacement blend is at the borderline of the specification for subbase material.

## 3.5 References

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# CHAPTER IV

# DURABILITY AGAINST WETTING-DRYING CYCLES OF LIGHTWEIGHT CEMENT STABILIZED MARGINAL LATERITIC/MELAMINE DEBRIS BLENDS FOR PAVEMENT APPLICATIONS

## 4.1 Introduction

Presently there is a scarcity of high quality pavement materials due to the rapid depletion of virgin quarry sources. Furthermore, haulage costs of high-quality quarry materials is exceedingly expensive. An alternative and sustainable manner is to stabilize the locally marginal soil with Portland cement. This technique is economical because cement is readily available at a reasonable cost in many countries including Thailand. Moreover, adequate strength can be achieved in a short duration of time (Horpibulsuk, et al., 2010). High plasticity marginal soils are typically blended with a non-plastic material before cement stabilization. The usage of recycled waste materials in blends with marginal soil is of international interest, given the many environmental benefits (Arulrajah et al., 2014a and b).

Several authors have researched on the utilization of various recycled materials in geotechnical and pavement applications. The usage of waste by-products in civil infrastructure enables an alternative to quarried materials resulting in conservation of natural resources, decreased energy use, and reduced greenhouse gas emission. In recent years, extensive research works on innovative and environmentally friendly solutions have resulted in the applications of green technologies in pavement construction, which have led to the more efficient use of natural resources and recycled materials (Moreno et al., 2012). The usage of recycled materials in pavement applications has significant economical and environmental impacts and has been recently researched (Arulrajah et al., 2014a and b; Kampala and Horpibulsuk, 2013; Kampala et al., 2013 and Phetchuey et al., 2014). For example, recycled plastic wastes were blended with demolition wastes to form pavement base materials (Arulrajah et al., 2017), spent coffee grounds were used as road embankment fills (Arulrajah et al., 2014c), cement-stabilized construction and demolition materials were used as pavement base and subbase materials (Mohammadinia et al., 2015), quarry waste was used in pavement applications (Guilian, et al., 2014 and Ribeiro de Rezende et al., 2014), calcium carbide residue and fly ash were used to improve the strength of problematic silty clay to be a subgrade material (Horpibulsuk, et al., 2012 and Kampala et al., 2014), crushed glass was used to replace a natural aggregates (Wartman et al., 2004) and recycled asphalt pavement and fly ash geopolymers were used as a pavement base material (Hoy et al., 2016b and 2017).

Melamine debris (MD) is a waste material resulting from the manufacturing process of plates and cups. MD cannot be reformed or reused for manufacturing plates and cups (Siwadamrongpong et al., 2012). It was reported by Srithai Superware Public Co., Ltd, a largest melamine tableware company in Thailand, that the company releases 400 tons of MD annually. Presently, this MD is disposed by burning at a very high temperature, which is costly and damages the air quality. MD is a non-plastic and coarse-grained waste material and has been successfully used as a replacement material to improve the engineering properties of marginal lateritic soil (LS) (Donrak et al., 2016). The MD could improve both physical and mechanical properties of marginal LS. The liquid limit and plasticity index of LS reduced with increasing MD replacement. With low LA abrasion of MD, the MD replacement enhanced the durability against traffic load to the marginal lateritic soil. With 10-50% replacement, the improved soil could be used as an engineering fill material according to the specification by the Department of Highways, Thailand.

In addition to unbound pavement applications, the MD can be used to adjust the gradation, improve plasticity and of marginal LS before cement stabilization. Cement stabilization is commonly used in practice because of high strength after short period of stabilization. However, the cementation bond degraded with the weather changes. The durability of stabilized materials under severe climatic conditions is a crucial parameter when used in road construction applications. The study on durability of cement stabilized LS/MD blends is however still in its infancy. Dempsey and Thompson (1967) defined durability as the ability of the materials to retain their stability and integrity and to maintain adequate long-term residual strength to provide sufficient resistance to climate conditions.

Cyclic wetting-drying (w-d) test, simulates weather changes over a geological age, and is considered to be one of the most appropriate simulations that can induce damage to pavement materials (Allam and Sridaran,1981 and Sobhan et al., 2007). Kampala et al. (2014) have investigated the influence of w-d cycles on the durability of

CCR-FA stabilized clays in pavement applications to ascertain its serviceability. The optimal CCR and FA contents were reportedly 7% and 20%, respectively. The strength of the CCR stabilized clay reduced significantly with the number of w-d cycles. Al-Obaydi et al. (2010) and Al-Zubaydi. (2010) indicated that the cyclic w-d cycles caused crack propagation, resulting in severe effects on the engineering properties of the materials, particularly in terms of their residual strength and stability.

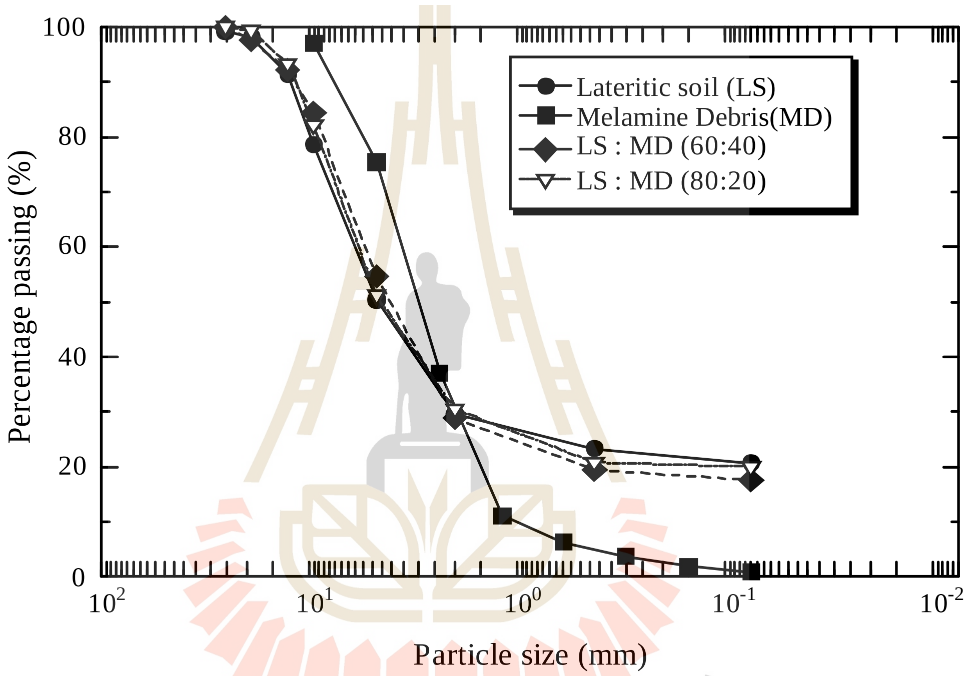
Although the utilization of stabilized LS/MD blends in highway construction can be considered as having significant impacts on resource management, the hazardous compounds that can leach out and pollute the water resource should also be assessed. The stabilized LS/MD blend must not pose any risk to the groundwater resources. A potential risk associated with the use of waste materials is the excessive release of heavy metals, as these are known to seriously endanger human health (Arurajah et al., 2015; Dawson, 2009 ; Zhuang et al., 2009). The most commonly used method to assess such associated risks is the Environmental Protection Agency (EPA)'s toxicity characteristic leaching procedure (TCLP). This is used by regulatory agencies for classifying hazardous waste, as well as by waste-disposal contractors to compare the leaching performance of different waste forms (Huang et al., 2016).

This research attempts to study the impact environmental assessment, density, strength and durability against wetting and drying (w-d) cycles of cement stabilized LS/MD blends. The strength change with the MD replacement is illustrated by the mineralogical and microstructural changes using the application of X-ray diffraction (XRD) and scanning electron microscopy (SEM) analyses. The change in the strength and physical properties of cement stabilized LS/MD blends at various cyclic w–d cycles were examined using unconfined compression strength (UCS) and weight loss tests. The outcome of this research will enable the development of construction guidelines for researchers, pavement engineers and end-users in assessing suitable cement stabilized LS/MD blends in future road construction applications.

## 4.2 Materials and methods

Marginal lateritic soil (LS) samples were obtained from a borrow pit in Maung district, Sakonnakhon province, Thailand (**Figure 4.1a**) at 1.5 meter depth. The lateritic soil was composed of 20.7% fine-grained particles and 79.3% coarse-grained particles in which 49.6% was gravel and 29.7% was sand. The bulk specific gravity of coarse-grained and fine-grained particles were 2.67 and 3.03, respectively and the liquid and plastic limits were 40.7% and 20.9%, respectively. According to the Unified Soil Classification System (USCS), the LS was classified as clayey gravel (GC).

The grain size distribution curve is shown in **Figure 4.2** and basic properties are summarized in **Table 4.1**. According to the Department of Highways specifications of Thailand for subbase material (DH-S205/2532) and for engineering fill material (DH-S208/2532), the California bearing ratio (CBR), swell and liquid limit (LL) of LS do not meet the required standards (**Table 4.2**). LS thus requires chemical stabilization, in order to be used as bound base, subbase and subgrade materials.


Lateritic soil (LS)
Melamine Debris(MD)
LS : MD (60:40)
LS : MD (80:20)
Percentage passing (%)
Particle size (mm)
100
80
60
40
20
0
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$

graded sand (SP) based on USCS. The bulk specific gravities of fine-grained and coarse-grained particles were 1.45 and 1.38, respectively.

**Table 4.1** Geotechnical properties of Lateritic soil, MD and Lateritic soil/MD blends.

| Sample Description | MD | Lateritic Soil : MD | | Lateritic Soil | Remark |
|---|---|---|---|---|---|
| | | 60:40 | 80:20 | | |
| LA abrasion value (%) | 11.3 | 43.3 | 50.4 | 59.2 | ASTM C131 ,C535 |
| LL. (%) | - | 38.4 | 39.8 | 40.7 | AASHTO T90 |
| PL. (%) | - | 25.8 | 23.2 | 20.9 | AASHTO T90 |
| PI. (%) | - | 12.6 | 16.6 | 19.8 | |
| $D_{10}$ (mm) | 0.90 | - | - | - | |
| $D_{30}$ (mm) | 2.00 | 2.10 | 1.90 | 2.10 | |
| $D_{50}$ (mm) | 3.00 | 3.80 | 4.50 | 4.50 | |
| $D_{60}$ (mm) | 3.80 | 5.30 | 5.80 | 6.00 | |
| $C_u$ | 4.22 | - | - | - | |
| $C_C$ | 1.17 | - | - | - | |
| Gravel size content(%) | 24.6 | 42.4 | 48.9 | 49.6 | Retained #4 |
| Sand size content(%) | 74.5 | 40.0 | 31.1 | 29.7 | Passed#4-Retain#200 |
| Fines size content(%) | 0.9 | 17.6 | 20.0 | 20.7 | Passed#200 |
| Classification-USCS | SP | GM | GC | GC | |
| Bulk specific gravity Coarse-grained | 1.38 | 2.08 | 2.20 | 2.67 | AASHTO T85-70 |
| Bulk specific gravity Fine-grained | 1.45 | 2.03 | 2.02 | 3.03 | AASHTO 84 |
| Apparent specific gravity Coarse-grained | 1.53 | 2.41 | 2.57 | 3.18 | AASHTO T85-70 |
| Apparent specific gravity Fine-grained | 1.69 | 2.51 | 2.53 | 3.47 | AASHTO 84 |
| Water absorption Coarse-grained | 6.99 | 6.61 | 6.58 | 5.95 | AASHTO T85-70 |
| Water absorption Fine- grained (%) | 9.72 | 9.32 | 9.93 | 4.19 | AASHTO 84 |



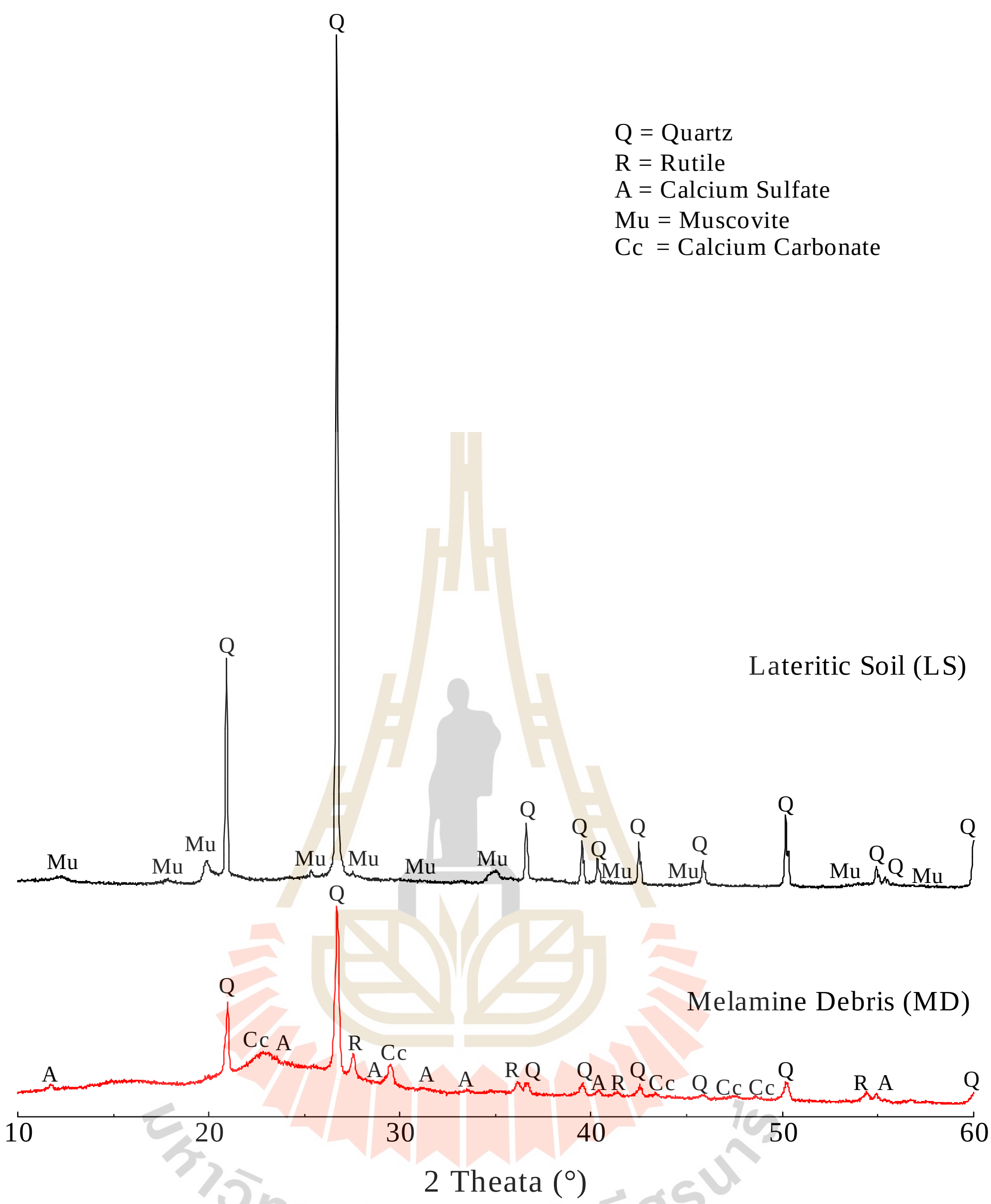
**Table 4.3** summarizes the chemical composition of MD using XRF analysis. MD was composed mainly of 26.65% $SiO_2$, 23.82% $TiO_2$, 20.90% $Fe_2O_3$, and 15.83% CaO. The peaks of main amorphous phases, including quartz, calcium carbonate, calcium sulfate, and rutile were detected by XRD analysis (**Figure 4.3**). The CaO in MD can react with silica and alumina in LS for an enhanced pozzolanic reaction. In this

research, 2 MD replacement ratios of 20% and 40% were selected for improving physical and mechanical properties of LS.

**Table 4.2** Material properties of lateritic soil/MD blends compared with requirements for engineering fill material and subbase materials.

| Sample Description | Sub-base Material (DH-S205/2532) | Engineering Fill Material (DH-S208/2532) | MD | Lateritic Soil (LS) |
|---|---|---|---|---|
| LA abrasion value (%) | $\leq$ 60 | $\leq$ 60 | 11.3 | 59.2 |
| California Bearing Ratio at 95% Max Dry Density(%) | $\geq$ 25 | $\geq$10 | - | 11.9* |
| Swell (%) | $\leq$ 4 | $\leq$ 3 | - | 5.27* |
| LL (%) | $\leq$ 35 | $\leq$ 40 | - | 40.7* |
| PI (%) | $\leq$ 11 | $\leq$ 20 | - | 19.8 |
| Remark | | | | *Not meet. |

**Table 4.1** presents the physical and mechanical properties of LS/MD blends at various MD replacement ratios. 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** **Figures 4.2** shows the particle size distribution curves of the LS/MD blends at 20% and 40% MD replacement compared with those of LS and MD. It is noted that the MD replacement increased the coarse contents and reduced the fine contents; therefore the reduction in plasticity index.


Q = Quartz
R = Rutile
A = Calcium Sulfate
Mu = Muscovite
Cc = Calcium Carbonate
Lateritic Soil (LS)
Melamine Debris (MD)
Q
Mu
Cc
A
R
10
20
30
40
50
60
2 Theata (°)

tests. All tests were undertaken following relevant American Association of State Highway and Transportation Officials (AASHTO) and American Society for Testing and Materials (ASTM).

**Table 4.3** Chemical composition of Lateritic soil and MD by using XRF analysis.

| **Chemical formula (%)** | **LS** | **MD** |
|---|---|---|
| $Na_2O$ | 0.70 | N.D |
| MgO | 0.84 | 0.36 |
| $Al_2O_3$ | 12.41 | 4.82 |
| $SiO_2$ | 65.08 | 26.65 |
| $P_2O_5$ | 0.86 | 1.37 |
| $SO_3$ | 0.07 | 3.28 |
| Cl | 0.40 | 0.18 |
| $K_2O$ | 4.21 | 1.06 |
| CaO | 1.01 | 15.83 |
| $TiO_2$ | 1.46 | 23.82 |
| $Cr_2O_3$ | 0.02 | 0.28 |
| MnO | 0.13 | 0.89 |
| $Fe_2O_3$ | 12.51 | 20.90 |
| CuO | 0.01 | 0.14 |
| $ZrO_2$ | 0.19 | 0.22 |
| LOI | 0.57 | 5.20 |



Modified compaction effort was used to determine the maximum dry density (MDD) and optimum moisture content (OMC) of the specimens. The modified compaction tests were conducted by following the AASHTO T 180. UCS test on cement stabilized LS/MD blends were performed after 7, 14 and 28 days of curing. The UCS samples were wrapped in vinyl bags and stored in a humidity-controlled room of constant temperature. The tests were run according to the American Standard for Testing and Materials ASTM D 1633 (ASTM 2000). CBR test method followed the AASHTO T 193. The CBR tests were carried out on the blends subjected to modified Proctor compaction effort at the OMC and soaked for 4 days to simulate the worst-case scenario (Arulrajah et al., 2014b).

The method of cyclic wetting and drying test as per ASTM D 559-03(ASTM 2003) was carried out on cylindrical samples with 152 mm in diameter and 116.43 mm in height. The cylindrical samples were wrapped in vinyl bags and stored in a humidity-controlled room of constant temperature until 28 days of curing before wetting and drying test. The samples were submerged in deionized water at room temperature for 5 h. The samples were then dried in the oven at a temperature of 70 $^{o}$C for 48 h and air-dried at room temperature for at least 3 h. This process is referred to as 1 w–d cycle. After attaining the target w–d cycles, the samples were immersed in deionized water for 2 h at the constant temperature of 25 $\pm$2 $^{o}$C. UCS test were then undertaken with a rate of vertical displacement of 1 mm/min. The 0, 3, 7 and 12 w–d cycles were considered in this study.

The microstructural change of stabilized LS/MD blends at various MD replacement ratios were illustrated by X-ray diffraction (XRD) and scanning electron microscopy (SEM) analyses. 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 (Miura et al., 1999; Horpibulsuk et al., 2010). All samples were coated with gold before SEM (JOEL JSM-6400) analysis. The XRD analyses were done on the powder samples, which were compacted in a Cu X-ray tube. The XRD traces were obtained by scanning at 0.1° (2θ) per min and at steps of 0.05°(2θ) (Hoy et al., 2016a).

The TCLP test is the method prescribed by the US EPA guidelines to determine whether the solid waste is hazardous (Townsend, 1998). The TCLP tests were assessed on MD and 5% cement stabilized LS/MD blends with 0% and 20% MD content. In the leachate test, the 28 days cured samples were crushed to smaller particles of smaller than 9.5 mm. The crushed sample was diluted using an acetic acid solution (pH = 4) in a volume with a solid to liquid ratio of 1:20. The mixture was agitated for 18 hours in an extraction vessel rotated in an end-over-end manner at 30 rounds per minute. The leachate was then filtered through a 0.45 μm membrane filter to remove suspended solids for determining the metal contents in the leachate using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) technique. The average values were obtained by testing in triplicate samples to ensure the data consistency.

## 4.3 Results and discussion

### 4.3.1 Density and Unconfined Compression Strength

Based on the Department of Highways specifications for stabilized base and subbase materials (**Table 4.4**), the gradation of the LS meets the requirement but LL is higher than the specification and must be reduced before the chemical stabilization. By replacing LS with 20% and 40% MD, all the index properties were improved (**Table 4. 4**) and meet the specification. The LA abrasion reduces from 59.2 to 43.3%, LL reduces from 40.7% to 38.4% and PI reduces from 19.8% to 12.6% when MD is replaced by 40%.

**Table 4.4** Compared between typical specification from Department of Highway, Thailand and test result.

| Sample Description | Stabilized Sub-base (DH-S206/2532) | Stabilized Base (DH-S204/2533) | Lateritic Soil : MD | | | MD |
|---|---|---|---|---|---|---|
| | | | 100:0 | 80:20 | 60:40 | |
| Gradation | Max. size $\leq$ 50 mm. | Max. size $\leq$ 50 mm. | 25.4 | 25.4 | 25.4 | 12.7 |
| | NS. | Passed#10 $\leq$ 70% | 29.5 | 30.5 | 28.8 | 30.0 |
| | Passed#200 $\leq$ 40% | Passed#200 $\leq$ 25% | 20.7 | 20.0 | 17.6 | 0.9 |
| LA (%) | NS. | $\leq$ 60 | 59.2 | 50.4 | 43.3 | 11.3 |
| LL (%) | $\leq$ 40 | $\leq$ 40 | 40.7* | 39.8 | 38.4 | - |
| PI (%) | $\leq$ 20 | $\leq$ 15 | 19.8 | 16.6 | 12.6 | - |
| NS. = Not specified. | | | *Not meet. | | | |

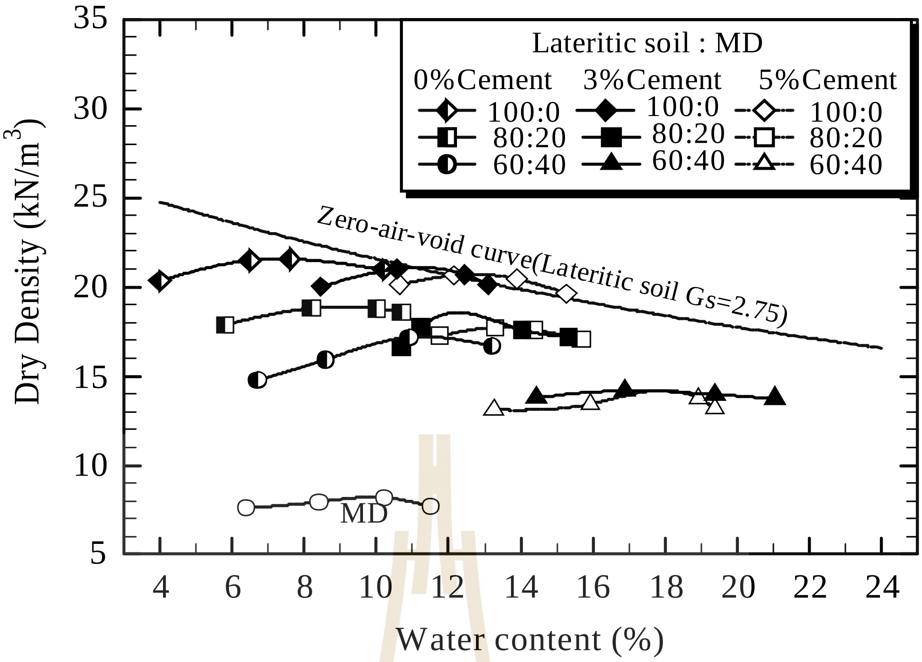
**Table 4.5** and **Figure 4.4** show the modified compaction test results of the stabilized LS/MD blends at various MD replacement ratios and cement contents compared with those of LS and MD. All compaction curves of LS/MD blends exhibit bell-shaped compaction pattern, typical of traditional geomaterials (Horpibuksuk et al., 2008 and 2009). The MDD of MD is relatively low (8.2 kN/m$^3$) compared to that of LS (21.6 kN/m$^3$). For a particular MD replacement ratio, the cement stabilization increases the OMC of the LS and LS/MD blends because of the higher water required for cement hydration. The higher cement content results in the higher OMC; i.e., the OMC values of LS are 7.6%, 11.0%, and 12.5% for 0% C, 3% C and 5% C, respectively. While the

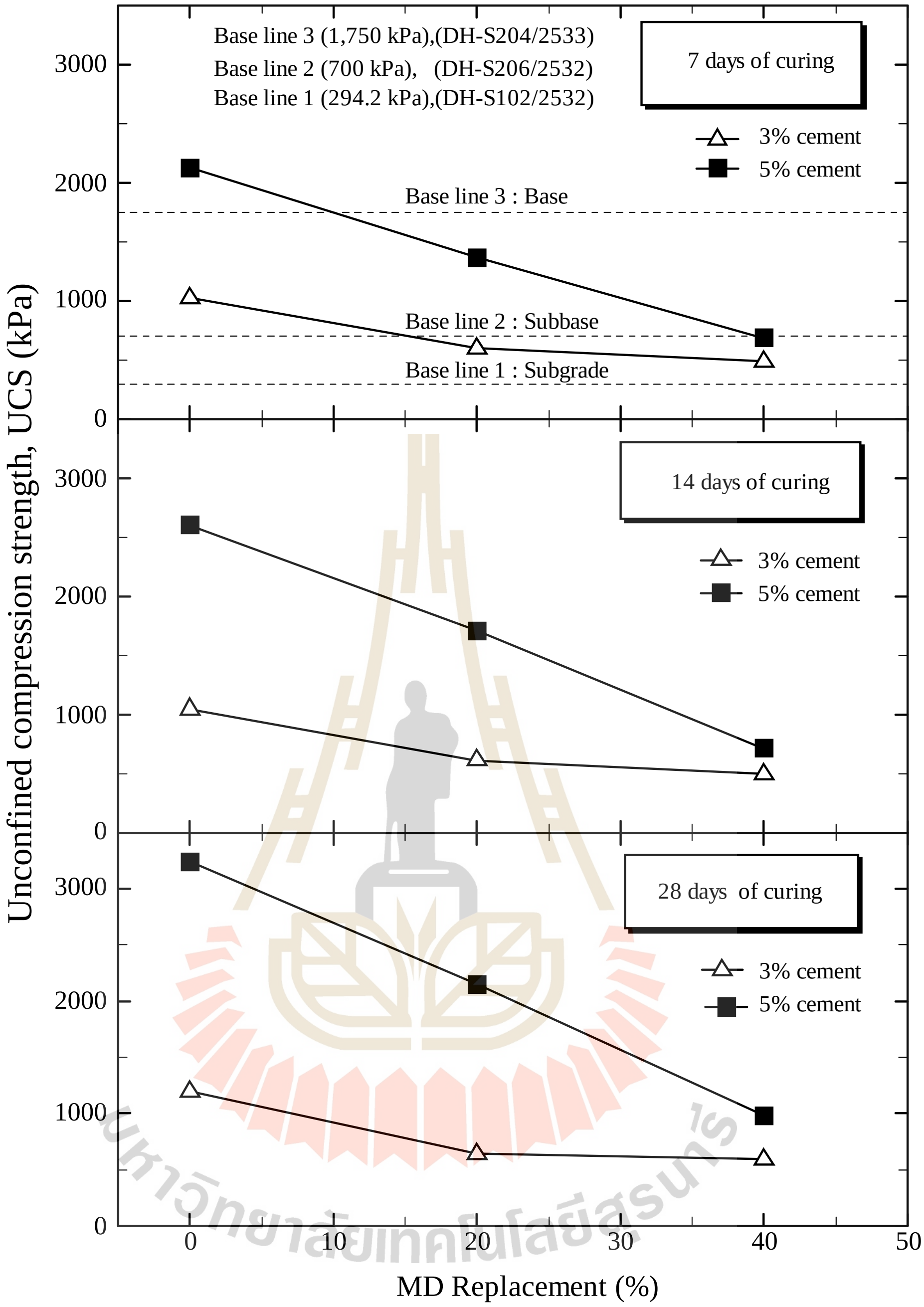
input of cement has minimal effect on the MDD of stabilized LS/MD blends similar to the finding by Horpibulsuk et al (2006).

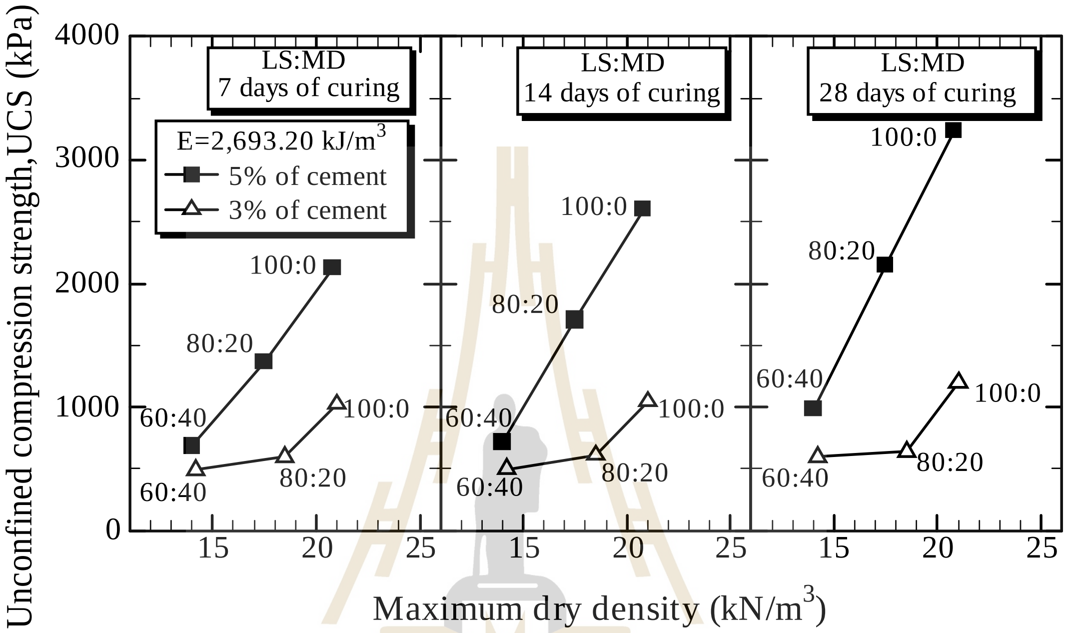
**Table 4.5** Modified Compaction Test and California Bearing Ratio of Lateritic soil , MD , Lateritic soil/MD blends And Lateritic soil/MD blends with Cement stabilized.

| Sample Description | Lateritic Soil : MD | | | | | | | | | MD | Remark |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0%Cement | | | 3%Cement | | | 5%Cement | | | | |
| | 100:0 | 80:20 | 60:40 | 100:0 | 80:20 | 60:40 | 100:0 | 80:20 | 60:40 | | |
| MDD (kN/m$^3$) | 21.6 | 18.9 | 17.3 | 21 | 18.5 | 14.2 | 20.8 | 17.5 | 14.0 | 8.2 | AASHTO T180 |
| OMC (%) | 7.6 | 9.0 | 12.5 | 11 | 11.5 | 16.5 | 12.5 | 13.0 | 17.5 | 10.0 | AASHTO T180 |
| California Bearing Ratio (Soaked 4 days) (%) | 11.9 | 18.3 | 20.0 | 44.4 | 57.2 | 48.1 | 52.9 | 89.5 | 52.5 | - | AASHTO T193 |
| Swell (Soaked 4 days) (%) | 5.27 | 1.41 | 0.35 | 0.72 | 0.38 | 0.11 | 0.30 | 0.18 | 0.08 | - | AASHTO T193 |

For a particular cement content, the increase in MD replacement increases OMC and reduces MDD significantly of the stabilized LS/MD blends; i.e., at C = 3%, OMC and MDD are 11% and 21 kN/m$^3$ for 0% MD, 11.5% and 18.5 kN/m$^3$ for 20% MD and 16.5% and 14.3 kN/m$^3$ for 40% MD, respectively. The reduction in MDD with increasing MD replacement is due to the very low unit weight of MD. This significant reduction in MDD can decrease the overburden on the foundation, which is an advantage over traditional stabilized pavement material.


Lateritic soil : MD
0%Cement
3%Cement
5%Cement
100:0
80:20
60:40
Zero-air-void curve(Lateritic soil Gs=2.75)
MD
Dry Density (kN/m3)
Water content (%)
35
30
25
20
15
10
5
4
6
8
10
12
14
16
18
20
22
24


Base line 3 (1,750 kPa),(DH-S204/2533)
Base line 2 (700 kPa), (DH-S206/2532)
Base line 1 (294.2 kPa),(DH-S102/2532)
7 days of curing
3% cement
5% cement
Base line 3 : Base
Base line 2 : Subbase
Base line 1 : Subgrade
14 days of curing
3% cement
5% cement
28 days of curing
3% cement
5% cement
Unconfined compression strength, UCS (kPa)
MD Replacement (%)
0
1000
2000
3000
0
10
20
30
40
50


Unconfined compression strength,UCS (kPa)
0
1000
2000
3000
4000
LS:MD
7 days of curing
E=2,693.20 kJ/m3
5% of cement
3% of cement
100:0
80:20
60:40
100:0
80:20
60:40
LS:MD
14 days of curing
100:0
80:20
60:40
100:0
80:20
60:40
LS:MD
28 days of curing
100:0
80:20
60:40
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60:40
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25
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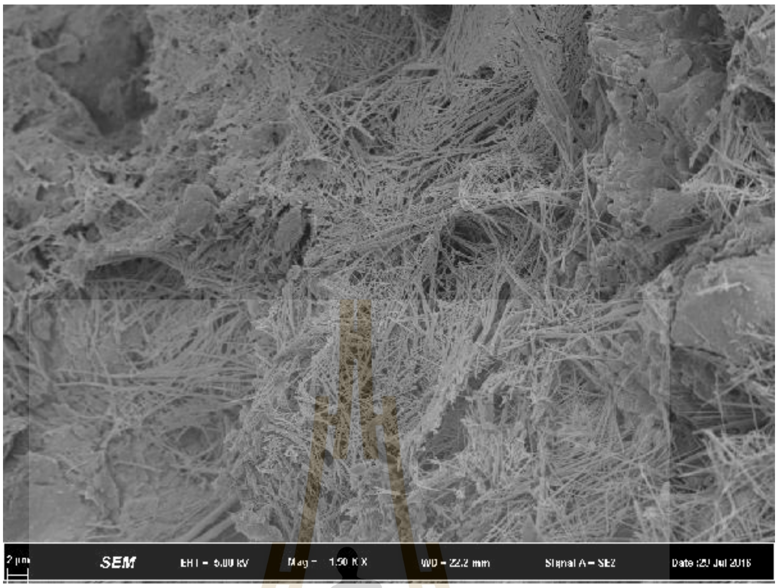
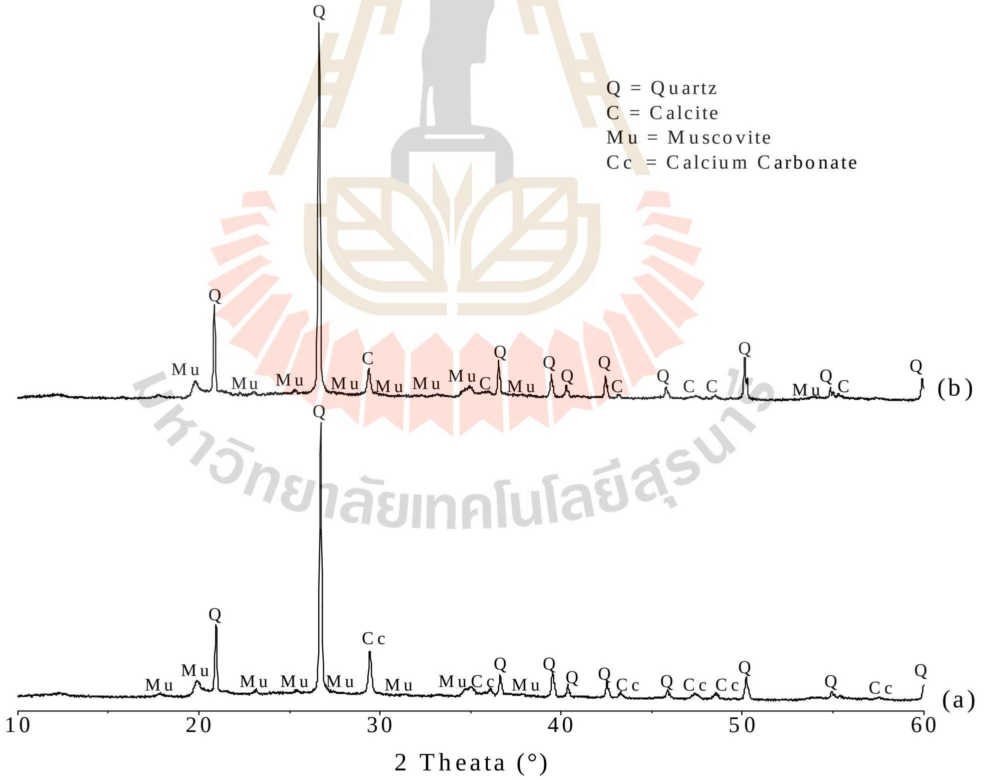
20
25
Maximum dry density (kN/m3)


2 μm
SEM
Signal A = SE2

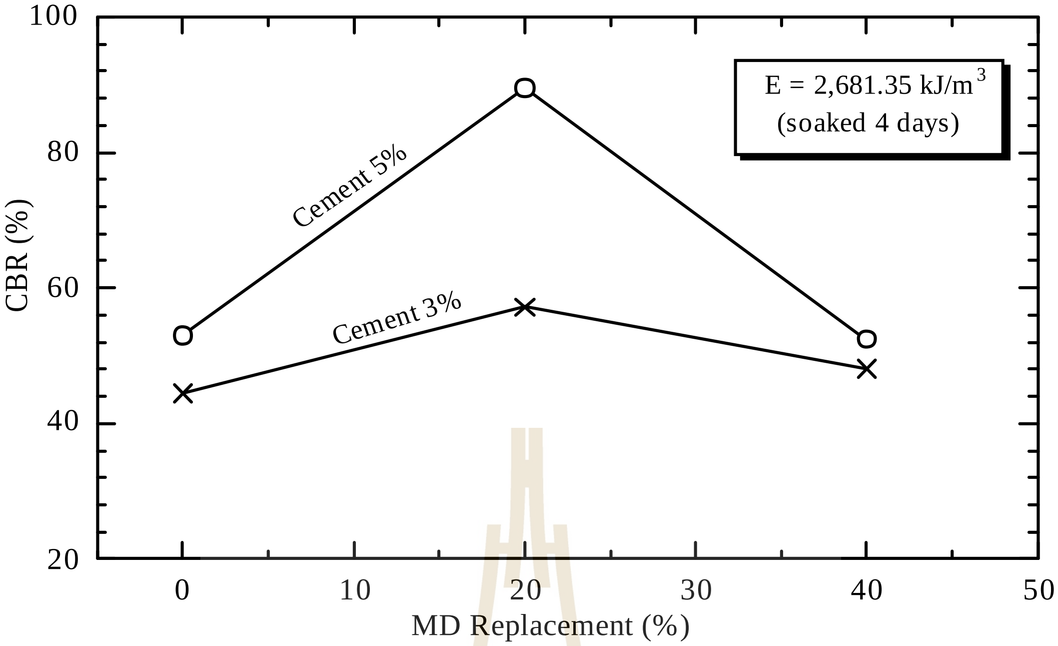

2 μm
SEM
Signal A = SE2

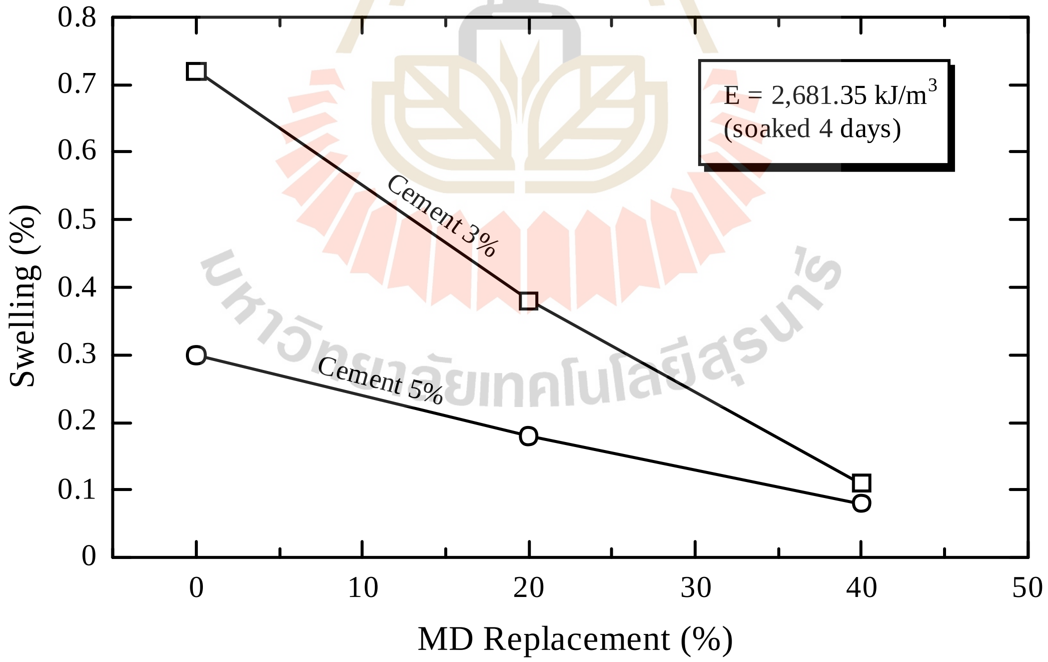


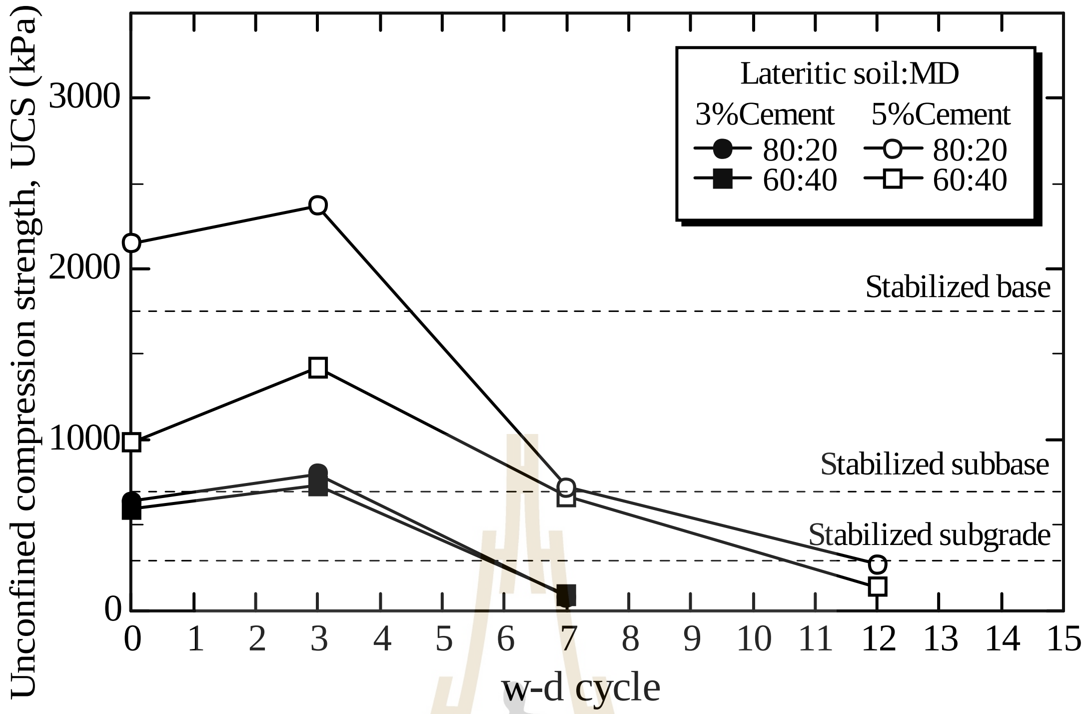
Q = Quartz
C = Calcite
Mu = Muscovite
Cc = Calcium Carbonate
(b)
(a)
2 Theata (°)

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

**Figure 4.9** shows the relationship between soaked CBR and MD replacement ratio. It is of interest that the CBR versus MD pattern is different from the UCS versus MD pattern. The soaked CBR increases with increasing MD replacement and decreases after the maximum value (the maximum soaked CBR is found at 20% MD) while the UCS decreases with increasing MD replacement. Even though the soaked CBR reduces after the maximum value (at 20% MD), the soaked CBR values of 40% MD samples are still higher than those of 0% MD samples for both C = 3% and 5%. This shows the advantage of MD replacement in developing a more durable lightweight material against soaking condition. This result implies that for serious immersion condition of 4 days, the stabilized LS/MD blends is more durable than the stabilized LS even with lower UCS. The higher soaked CBR value might be because MD minimizes the swelling pressure under long-term immersion condition. The higher swelling pressure leads to the lower load bearing capacity due to the break-up of cementation bond. The swelling pressure is directly related to swelling of stabilized LS/MD blends under the same sitting load of 2.54 kPa in CBR test as presented in **Figure 4.10** for various MD replacement ratios and cement contents. It is evident that the MD replacement reduces the swelling for both 3% and 5% C; hence, lower swelling pressure. Without MD replacement, the swelling values are high as 0.72% and 0.30% for 3% and 5% content, respectively. The relationship between swelling and MD replacement almost linear for both C = 3% and 5%.


E = 2,681.35 kJ/m3
(soaked 4 days)
Cement 5%
Cement 3%
CBR (%)
MD Replacement (%)


E = 2,681.35 kJ/m3
(soaked 4 days)
Cement 3%
Cement 5%
Swelling (%)
MD Replacement (%)

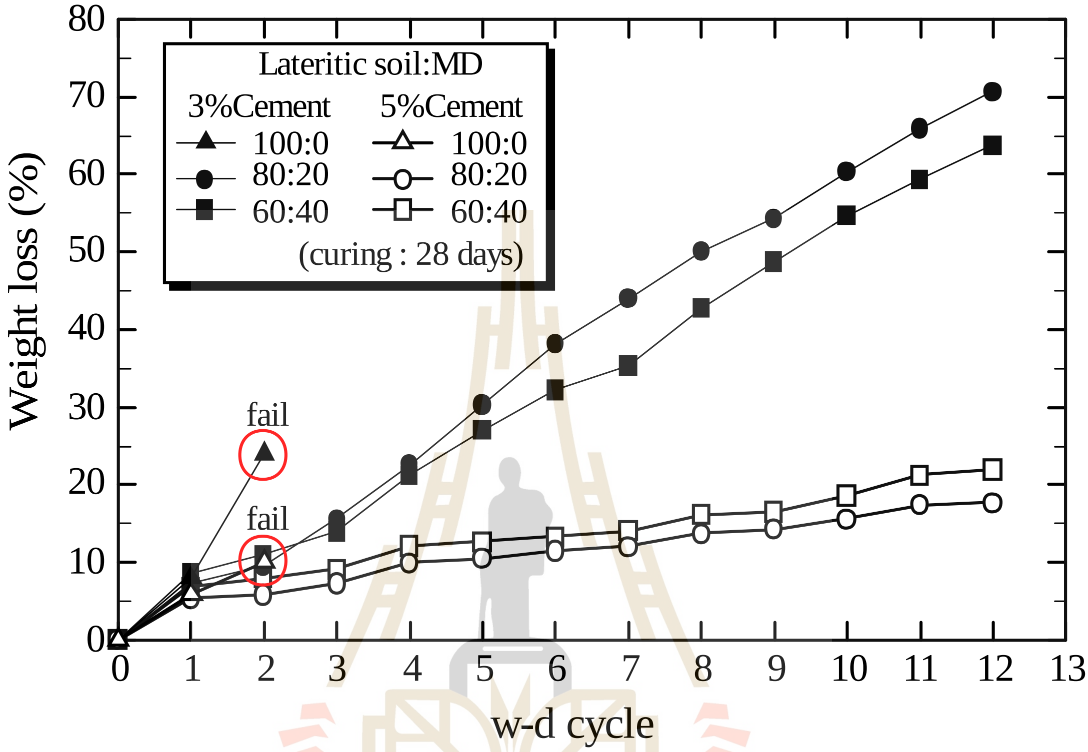

Lateritic soil:MD
3%Cement
5%Cement
80:20
60:40
80:20
60:40
Stabilized base
Stabilized subbase
Stabilized subgrade
Unconfined compression strength, UCS (kPa)
w-d cycle
0
1000
2000
3000
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

formation of calcium hydrates due to the presence of $Ca^{+2}$, $OH^{-}$ and $SiO_4$ and $AlO_6$ ions (from soil particles). Also drying at 70°C for w-d test evidently enhances the cementitious products (C-A-S-H) (Brue et al., 2012 and Jiang and Yuan, 2013); i.e., an increased temperature results in a faster moisture diffusivity of the cementitious materials and hence fast chemical reaction (Jooss and Reinhardt, 2002; Drouet et al., 2015; Wang et al., 2016).

For $N$ > 3, the integrity of the samples was not preserved; i.e., the samples gradually crumbled, fragmented and splintered. Deterioration and crack propagation occurs due to the desiccation kinetics causing the loss of the moisture (Aldaood et al., 2014 and Hoy et al, 2017). Following by the wetting process, the available pore spaces and cracks are filled with water. As such, the UCS increase due to the growth of cementitious products up to $N$ = 3 and then decrease onward. Similar observations were reported by Cuisinier et al. (2011) and Hoy et al. (2017) on soil stabilized with lime and recycled asphalt pavement stabilized with geopolymer, respectively.

The UCS values of 5% C samples are higher those at 3% for both 20% and 40%MD replacement for all $N$ tested. It is notable that although the 3% and 5% C stabilized LS (without MD replacement) possesses higher UCS than the 3% and 5% C stabilized blends, all the 3% and 5% C stabilized LS samples fail after the 3rd cycle. The MD replacement improves the durability against w-d cycles significantly.

The degradation of stabilized LS/MD blends due to w-d cycles can be observed by weight loss and surface cracks. The relationship between the weight loss of cement stabilized LS/MD blends at various $N$ is illustrated in **Figure 4.12**. The weight loss of 3% and 5% C samples for both 20% and 40% MD replacement increases significantly



Lateritic soil:MD
3%Cement
100:0
80:20
60:40
5%Cement
100:0
80:20
60:40
(curing : 28 days)
fail
fail
Weight loss (%)
w-d cycle
0
10
20
30
40
50
60
70
80
0
1
2
3
4
5
6
7
8
9
10
11
12
13


(a) 3% C and 20% MD


(b) 3% C and 40% MD


(c) 5% C and 20% MD


(d) 5% C and 40% MD

Although the UCS of cement stabilized LS meets the specification of Department of Highways, Thailand; 3% C for stabilized subbase and 5% C for stabilized base, the w-d cycle test results indicates that the 3% and 5% cement stabilized samples fail after the $2^{nd}$ w-d cycle and the UCS is almost zero after the first w-d cycle. The MD replacement can prolong the service life of the stabilized material up to three cycles. The 3% C with 20% and 40% MD can be used as lightweight stabilized subgrade material while the 5% C with 20% MD can be used as lightweight stabilized base material and 5% C with 40% MD can be used as lightweight stabilized subbase material.

### 4.3.3 Impact Environmental Assessment

To be used as a sustainable material, even due to rainfall or stormwater events, the cement stabilized LS/MD blends must not pose any risk to the groundwater tables or water streams beyond. Therefore, in order to use the cement stabilized LS/MD blends in road construction, the environmental risk assessment needs to be ascertained. **Table 4.6** shows the measured leachate heavy metal concentrations for MD, 5% C stabilized LS and 5% C stabilized LS/MD blends 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 4.6** indicates that all metal contaminants are within allowable limits.

**Table 4.6** Leachate analysis data for MD, LS and 5% C stabilized LS/MD blend.

| Parameter | Samples of acid leachate extraction (mg/L) | | | Drinking water regulations (EPA, 2009a) (mg/L) |
|---|---|---|---|---|
| | MD | 5% C stabilized LS | 5% C stabilized LS/MD blend | |
| pH | 3.16 | 4.37 | 4.39 | 6.5 - 8.5 |
| Arsenic | BDL | BDL | BDL | 0.01 |
| Cadmium | BDL | BDL | BDL | 0.005 |
| Chromium | BDL | 0.058 | 0.057 | 0.1 |
| Copper | BDL | BDL | BDL | 1.0 |
| Lead | BDL | BDL | BDL | 0.015 |
| Mercury | BDL | BDL | BDL | 0.002 |
| Nickel | BDL | 0.042 | 0.038 | - |
| Zinc | 2.63 | 0.067 | 0.099 | 5.0 |
| BDL = Below Detection Limit(<0.01 mg/L) | | | | |

The results indicate that 5% C stabilized LS/MD blend is mechanically and economically viable for use in pavement base/subbase applications. Besides good mechanical properties, the 5% C stabilized LS/MD 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 research evaluates the effect of cement content and MD replacement on density, UCS and durability against w-d cycles of cement stabilized LS/MD blends. The MD is a non-plastic waste material, which can be used as a blended material to improve gradation and swelling characteristics of LS prior to cement stabilization. The UCS values at various w-d cycles of stabilized LS/MD blends are compared with the specification of Department of Highways, Thailand for stabilized subgrade, subbase and base materials. The conclusions can be drawn as follows:

1. The density of LS/MD blends decreases with increasing MD replacement due to the low specific gravity of MD. The decrease in density is associated with the decrease in UCS. Due to the high water absorption of MD, the OMC of cement stabilized LS/MD blends increases with MD replacement ratio. As such, for the same input of cement, the cement stabilized LS/MD blend with higher MD replacement ratio possesses higher water to cement ratio, which results in lower cementitious products and lower UCS.
2. The relationship between UCS and density is exponential for 3% C stabilized LS/MD blends and linear for 5% C stabilized LS/MD blends. The density of cement stabilized LS/MD blends reduces to approximately 14 kN/$m^3$ when 40% MD is used. As such, the stabilized LS/MD blends provide lower overburden of the pavement structure on foundation than the conventional pavement materials.
3. Due to the reduction in swelling pressure of stabilized LS/MD blends by MD replacement, the soaked CBR of stabilized LS/MD blends is higher than that of stabilized LS for the same cement content. The lower swelling results in the lower break-up of the cementation bonding. The optimum MD replacement ratio providing the highest CBR is found to be at 20%.
4. Even though the UCS of cement stabilized LS meets the specification of Department of Highways, Thailand, the UCS is very low, almost zero, after the first w-d cycle. The 3% C with 20% and 40% MD can be used as lightweight stabilized subgrade material while the 5% C with 20% MD can be used as

lightweight stabilized base material and 5% C with 40% MD can be used as lightweight stabilized subbase material.

5. This study confirms the potential use of the cement stabilized LS/MD blends as a sustainable lightweight pavement material with high durability against w-d cycles. The use of MD furthermore results in significant reduction in greenhouse gas emission.

6. From an environmental perspective, the TCLP results indicated that the 5% C stabilized LS/MD blend 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 MD can be used as an environmentally friendly construction material in pavements.

## 4.5 References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# CHAPTER V

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Summary and conclusions

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

### 5.1.1 Possibility of using MD as replacement material to improve mechanical properties of marginal lateritic soil

Due to the low LA abrasion (of 11.3%) of MD, the MD replacement enhances the durability against traffic load to the marginal lateritic soil (LS). The unit weight of blends decreases with increasing MD replacement because of the low specific gravity of MD.  Even though the water absorption of blends increases with increasing MD replacement, the swelling decreases with increasing MD replacement ratio because MD is non-plastic material. The rate of swelling reduction with MD replacement is essentially the same for all compaction energy values tested. This chapter indicates that MD replacement can improve the geotechnical property requirement for engineering fill material according to national local authority. With 20% MD replacement, the physical and mechanical properties of blends meet the requirement. The 50% MD replacement blend is at the borderline of the specification for subbase material.

**5.1.2 Durability and engineering properties of marginal lateritic soil improved by melamine debris and Portland cement for pavement application**

LS, is typically blended with non-plastic materials to improve its gradation and swelling characteristics and subsequently stabilized with Portland cement to form pavement subbase and subgrade materials. MD can be used as a blended non-plastic material. The density of LS/MD blends decreases with increasing MD replacement due to the low specific gravity (1.38-1.69) of MD. , By replacing LS with 20% and 40% MD, all the index properties and gradation of LS are improved and meet the Department of Highways specifications for stabilized base and subbase materials. Although the UCS of cement stabilized LS meets the specification of Department of Highways, Thailand, the UCS is very low, almost zero, after the first w-d cycle. The 3% C with 20% and 40% MD can be used as lightweight stabilized subgrade material while the 5% C with 20% MD can be used as lightweight stabilized base material and 5% C with 40% MD can be used as lightweight stabilized subbase material. This study confirms the potential use of the cement stabilized LS/MD blends as a sustainable lightweight pavement material with high durability against w-d cycles.

**5.1.3 Environmental assessment of cement stabilized marginal lateritic soil/melamine debris blends for pavement applications**

To be used as a sustainable material, even due to rainfall or stormwater events, the cement stabilized LS/MD blends must not pose any risk to the groundwater tables or water streams beyond. Therefore, in order to use the cement stabilized LS/MD blends in road construction, the environmental risk assessment needs to be ascertained. The results indicate that 5% cement LS/MD blends at 20%MD can be safely used in sustainable pavement subbase applications. In addition, the leachability of heavy metals (chromium and nickel) is reduced when MD is used to blends with LS. This study indicates that MD can be considered as an environmentally friendly pavement material.

## 5.2 Recommendations for future work

- Study a field performance of cement stabilized LS/MD blends
- Develop a design method for road pavement using cement stabilized LS/MD blends
- Study the possibility of using MD as replacement in of cement stabilized recycled materials.
- It is recommended to study SEM at different ages of curing time all samples.
- Study on the effect of water content on engineering and mechanical properties of materials, it is interesting.
- It is recommended to the field research using the data from this study to confirm the implementation is actually assured.

# APPENDIX A

# LIST OF PUBLICATIONS

## List of Publications


Donrak, J., and Horpibulsuk, S., **A Study on Physical and Geotechnical Properties of Melamine Debris 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.

Donrak, J., Rachan, R., Horpibulsuk, S., Arulrajah, A., & Du, Y. J. 2016. **Improvement of marginal lateritic soil using Melamine Debris replacement for sustainable engineering fill materials**. Journal of Cleaner Production, 134, Part B, 515-522 (IF2014 = 3.844).

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

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

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# Improvement of marginal lateritic soil using Melamine Debris replacement for sustainable engineering fill materials

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Mechnical properties

ABSTRACT

This research evaluates the physical and mechanical properties of marginal lateritic soil and Melamine Debris (MD) blends as a sustainable engineering fill material. Physical property tests included specific gravity, water absorption, Atterberg limits, Los Angeles (LA) abrasion and particle-size distribution, while mechanical property tests included California Bearing Ratio (CBR) and swelling. The results indicate that MD as non-plastic coarse-grained and durable material (LA = 11.3%) can be used as an alternative replacement material for engineering fill materials. The MD replacement of lateritic soil reduces the fine content and increases the abrasion resistance of the soil particles, hence the reduction in liquid limit, plasticity index, LA abrasion and particle breakage. This physical property improvement leads to superior mechanical properties (soaked CBR and swelling) with increasing MD replacement ratio as compared to the soil alone. The proposed empirical equations for predicting soaked CBR and swelling of blends at different MD replacement ratios and compaction energy levels are useful in the selection of the suitable MD replacement to attain targeted mechanical property requirements. The physical and mechanical properties of the 20% MD replacement blend were found to meet the requirement of local road authority for engineering fill materials while the 50% MD replacement blend was at the borderline for a subbase course material.



## 1. Introduction

Quality pavement subbase/base and engineering fill materials are becoming increasingly scarce to source for road infrastructure projects. Therefore, modification of soils on site is an attractive and economical option to improve their mechanical properties (Chinkulkijniwat and Horpibulsuk, 2012; Horpibulsuk et al., 2006, 2011, 2013 and Du et al., 2013, 2014). The most common soil improvement technique is to compact the locally available soil blended with high quality materials. Compaction is a practical and economical technique to improve the mechanical properties of soils by the application of either static or dynamic force (Horpibulsuk et al., 2008, 2009 and Bo et al., 2014). The usage of recycled materials blended with high quality materials to stabilize marginal soils has significant engineering, economical and environmental

*Abbreviations:* AASHTO, American Association of State Highway and Transportation Officials; ASTM, American Society for Testing and Materials; CBR, California Bearing Ratio; $CBR_{MD}$, Soaked CBR at different melamine debris replacement ratios; $CBR_0$, Soaked CBR at 0% melamine debris replacement; $C_c$, Coefficient of curvature; $C_u$, Uniformity coefficient; $D_{10}$, Grain diameter at 10% passing; $D_{30}$, Grain diameter at 30% passing; $D_{50}$, Grain diameter at 50% passing; $D_{60}$, Grain diameter at 60% passing; E, Compaction energy; $I_p$, Plasticity index; LA, Los Angeles; MD, Melamine Debris; MDD, Maximum dry density; OMC, Optimum moisture content; SC, Clayey sand; SM, Silty sand; $S_{MD}$, Swelling at different MD replacement ratios; $S_0$, Swelling at 0% MD replacement; SP, Poorly graded sand; USCS, Unified Soil Classification System; $w_L$, Liquid limit; $w_p$, Plasticity limit.

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benefits (Arulrajah et al., 2014a,b; Kampala and Horpibulsuk, 2013; Kampala et al., 2013 and Phetchuay et al., 2014).

Recent usages of recycled materials in pavement applications includes recycled glass for pavement and footpath bases (Disfani et al., 2014; Arulrajah et al., 2013, 2014a,b and 2015), spent coffee ground in road work embankments (Arulrajah et al., 2014c, 2015b), construction and demolition materials used with geotextile in permeable pavements (Rahman et al., 2015), overburnt distorted bricks as aggregates for pavement courses (Mazumder et al., 2006), sand reinforced with plastic wastes (Consoli et al., 2002) and crushed brick as supplementary material in bound pavement (Disfani et al., 2014).

Melamine Debris (MD) is an industrial waste resulting from plate and cup manufacture. This MD cannot be reprocessed for manufacturing plates and cups (Siwadamrongpong et al., 2012). It was reported by Srithai Superware Public Co., Ltd, a largest melamine tableware company in Thailand, that the company releases 400 tons of MD annually. Presently, this MD is disposed by combustion at a very high temperature, which is costly and has significant negative environmental effects. The sustainable usage of MD in civil engineering applications will provide a lower carbon footprint and result in positive social and economical impacts for governments, industry and consumers.

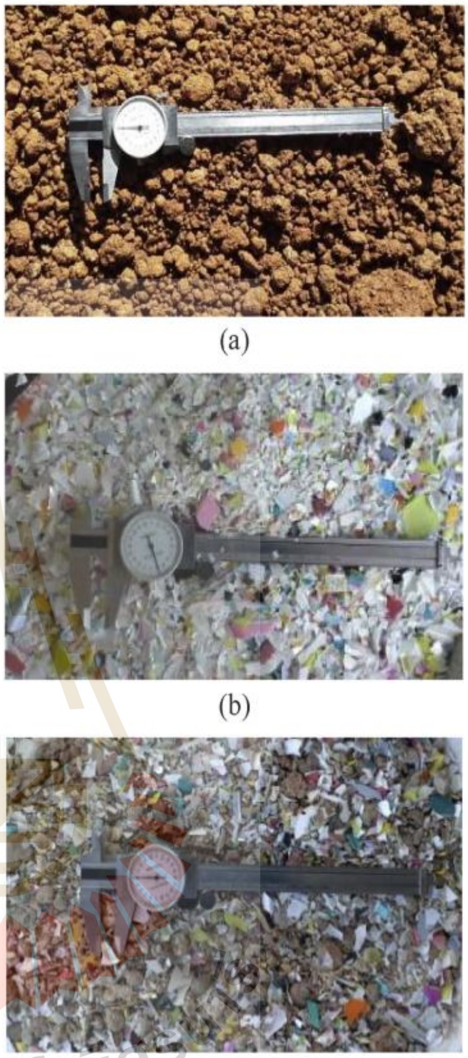
The usage of MD in marginal soil improvement for pavement application is innovative and of interest to the industrial sectors and national road authorities, particularly as road construction typically requires a large quantity of quality material. This paper investigates physical and mechanical properties of marginal lateritic soil blended with MD at various replacement ratios to ascertain it as an engineering fill material. This research will enable MD traditionally disposed to landfill, to be used in a sustainable manner as a non-plastic replacement material for marginal soil (high fine content) improvement.

## 2. Materials and methods

Marginal lateritic soil samples were collected from a borrow pit in Maung district, Sakonnakhon province, Thailand (Fig. 1a) at approximately 1.5 m depth. The lateritic soil is composed of 21.7% fine-grained particles and 78.3% coarse-grained particles in which 25.6% is gravel and 31% is sand. The specific gravity of coarse-grained particles is 2.67 and the liquid and plastic limits are 40.7% and 20.9%, respectively. According to the Unified Soil Classification System (USCS), the lateritic soil is classified as clayey sand (SC). The grain size distribution curve is shown in Fig. 2 and basic properties are summarized in Table 1. According to the local road authority specifications for subbase (DH-S205/2532) and for engineering fill materials (DH-S208/2532), this lateritic soil does not meet the requirement of the local standards, and will require blending with a higher quality material if it is to be considered as a pavement subbase or fill material.

Melamine Debris (MD) was obtained from Srithai Superware Public Co., Ltd, Nakhon Rachasima, Thailand. MD particles are shown in Fig. 1b. The grain size distribution of MD (Fig. 2) shows that MD is composed of 0.9% fine-grained particles and 99.1% coarse-grained particles. It is a non-plastic material and is classified as poorly graded sand (SP) based on USCS. The bulk specific gravities of fine-grained and coarse-grained particles are 1.45 and 1.38, respectively.

The laboratory evaluation program on marginal lateritic soil/MD blends included specific gravity, water absorption, Atterberg limit, particle-size distribution, modified Proctor compaction, Los Angeles (LA) abrasion, California Bearing Ratio (CBR) and swelling tests. All tests were undertaken following relevant American Association of State Highway and Transportation Officials (AASHTO) and American Society for Testing and Materials (ASTM). The lateritic soil: MD ratios studied were 100:0, 50:50, 60:40, 70:30, 80:20, 90:10 and 0:100. Fig. 1c shows the particles of lateritic soil/MD blend at 50:50 ratio.



(a) (b) (c)

Fig. 1. Photos of (a) Melamine Debris (MD) (b) Lateritic Soil (c) Lateritic soil/MD blends at 50:50 ratio.

The specific gravity and water absorption tests were performed in accordance with AASHTO T85-70 and AASHTO T 84, respectively. 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. The particle size distribution analysis and Atterberg tests were conducted on samples both

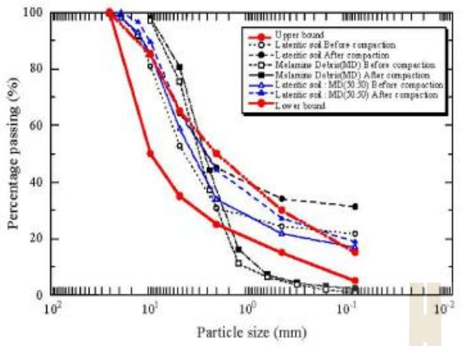



**Fig. 2.** Particle size distribution of lateritic soil/MD blend at 50% MD replacement.

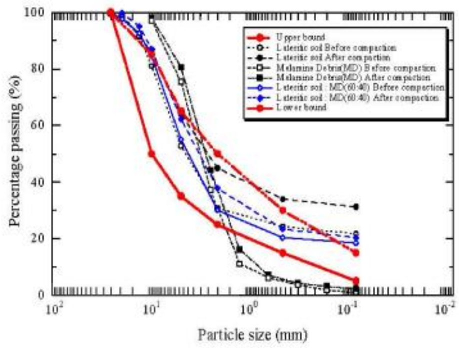



**Fig. 3.** Particle size distribution of lateritic soil/MD blend at 40% MD replacement.

before and after modified compaction tests to investigate the particle breakage due to compaction.

Modified compaction effort was used to determine the maximum dry density (MDD) and optimum moisture content (OMC) of the lateritic soil/MD blends. The modified compaction tests were conducted by following the AASHTO T 180. 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) was investigated in accordance with AASHTO T 193. The CBR tests were carried out on the blends subjected to modified Proctor compaction effort at the optimum water content and soaked for 4 days to simulate the worst-case scenario (Arulrajah et al., 2014b).

## 3. Results

### 3.1. Physical properties

Since MD is classified as a non-plastic material, MD replacement can increase the coarse-grained material contents and subsequently reduce plasticity of the marginal lateritic soil. Table 1 presents the physical and mechanical properties of lateritic soil/MD blends at various MD replacement ratios. The water absorption of coarse-grained MD (=6.99%) is slightly higher than that of lateritic soil (=5.95%) while the water absorption of fine grained MD (=9.72%) is 2.3 times higher than that of lateritic soil (=4.19%). As such, the water absorption values of both coarse and fine grains for the lateritic soil/MD blends increase with increasing MD replacement ratio. However, the specific gravities of the blends decrease with increasing MD replacement ratio due to lower bulk and apparent specific gravities of MD.

The grain size distribution parameters including $D_{10}$, $D_{30}$, $D_{50}$, $D_{60}$, $C_u$, $C_c$, and gravel, sand, and fine contents are also summarized in Table 1. Figs. 2–6 show the particle size distribution curves of the lateritic soil/MD blends at MD replacement ratios of 50%, 40%, 30%, 20% and 10%, respectively compared with the upper and lower boundaries of subbase materials specified by the Department of Highways, Thailand. It is noted that the MD particles larger than 3.80 mm ($D_{60}$) are above the upper boundary and MD particles finer than 1.05 mm ($D_{20}$) are below the lower boundary.

The results indicate that MD replacement reduces fine content of the lateritic soil. Almost all particle sizes of the lateritic soil/MD

**Table 1**
Physical and mechanical properties of marginal lateritic soil, MD and lateritic soil/MD blends before modified compaction test.

| Sample description | MD | Lateritic soil: MD | | | | | Lateritic soil | Remark |
|---|---|---|---|---|---|---|---|---|
| | | 50:50 | 60:40 | 70:30 | 80:20 | 90:10 | | |
| Bulk specific gravity Coarse-grained | 1.38 | 2.01 | 2.08 | 2.21 | 2.20 | 2.19 | 2.67 | AASHTO T85-70 |
| Bulk specific gravity Fine-grained | 1.45 | 1.98 | 2.03 | 2.17 | 2.02 | 2.29 | 3.03 | AASHTO 84 |
| Apparent specific gravity Coarse-grained | 1.53 | 2.32 | 2.41 | 2.57 | 2.57 | 2.54 | 3.18 | AASHTO T85-70 |
| Apparent specific gravity Fine-grained | 1.69 | 2.44 | 2.51 | 2.73 | 2.53 | 2.86 | 3.47 | AASHTO 84 |
| Water absorption Coarse-grained | 6.99 | 6.64 | 6.61 | 6.40 | 6.58 | 6.34 | 5.95 | AASHTO T85-70 |
| Water absorption Fine-grained (%) | 9.72 | 9.59 | 9.32 | 9.56 | 9.93 | 8.65 | 4.19 | AASHTO 84 |
| LA abrasion value (%) | 11.3 | 41.1 | 43.3 | 47.6 | 50.4 | 51.4 | 58.1 | ASTM C131,C535 |
| $w_L$ (%) | – | 37.8 | 38.4 | 38.9 | 39.8 | 39.9 | 40.7 | AASHTO T90 |
| $w_p$ (%) | – | 26.7 | 25.8 | 23.8 | 23.2 | 22.9 | 20.9 | AASHTO T90 |
| $I_p$ (%) | – | 11.1 | 12.6 | 15.1 | 16.6 | 17.0 | 19.8 | |
| $D_{10}$ (mm) | 0.90 | – | – | – | – | – | – | |
| $D_{30}$ (mm) | 2.00 | 1.25 | 2.00 | 0.85 | 1.50 | 1.20 | 1.80 | |
| $D_{50}$ (mm) | 3.00 | 3.50 | 4.00 | 3.50 | 3.80 | 3.50 | 4.50 | |
| $D_{60}$ (mm) | 3.80 | 4.75 | 5.20 | 5.00 | 5.30 | 4.90 | 5.50 | |
| $C_u$ | 4.22 | – | – | – | – | – | – | |
| $C_C$ | 1.17 | – | – | – | – | – | – | |
| Gravel size content (%) | 24.6 | 41.3 | 41.8 | 41.9 | 44.2 | 40.9 | 47.3 | Retained#4 |
| Sand size content (%) | 74.5 | 41.8 | 36.8 | 36.9 | 35.9 | 38.9 | 31.0 | Passed#4-Retain#200 |
| Fines size content (%) | 0.9 | 16.9 | 18.4 | 21.2 | 19.9 | 20.2 | 21.7 | Passed#200 |
| Classification-USCS | SP | SM | SM | SM | SC | SC | SC | |

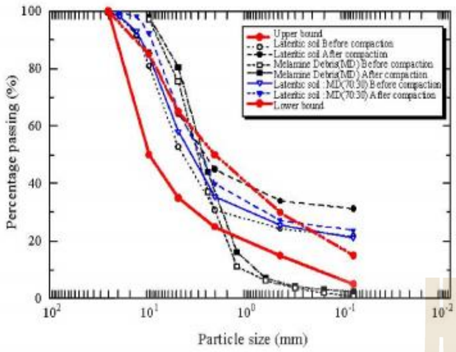



**Fig. 4.** Particle size distribution of lateritic soil/MD blend at 30% MD replacement.

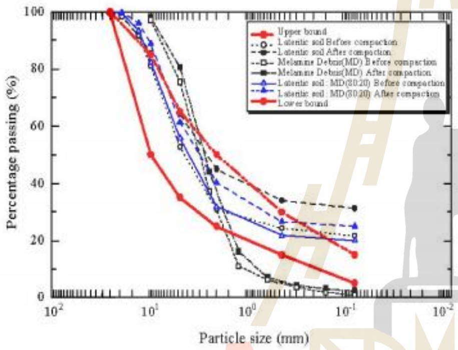



**Fig. 5.** Particle size distribution of lateritic soil/MD blend at 20% MD replacement.

blend at 50% MD replacement are within the acceptable boundaries for subbase materials except the fine content being slightly higher than upper boundary (15%). This blend is potentially suitable as a subbase material if more MD replacement (>50%) is used. Even though the gradation of all tested blends does not meet this specification, the fine content is reduced significantly with increasing

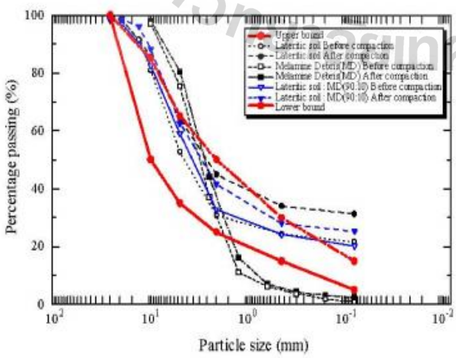



**Fig. 6.** Particle size distribution of lateritic soil/MD blend at 10% MD replacement.

MD replacement ratio and can be possibly used as the engineering fill material. Due to the reduction in fine content, the liquid limit ($w_L$) and plasticity index ($I_p$) reduce; i.e., $w_L$ is 39.9%, 39.8%, 38.9%, 38.4% and 7.8% and PI is 17.0, 16.6, 15.1, 12.6 and 11.1 for MD replacement ratios of 10%, 20%, 30%, 40% and 50%, respectively. Consequently, the lateritic soil/MD blends approach to a silty material type with increasing MD replacement ratio; i.e., they are classified as SM, SM, SM, SC and SC for MD replacement ratios of 10%, 20%, 30%, 40% and 50%, respectively while the lateritic soil is classified is SC. It is noted that $w_L$ and $I_p$ of these blends meet the consistency limits specified for engineering fill materials ($w_L < 40\%$ and $I_p < 20\%$).

Besides the Atterberg limits and gradation, the durability of the lateritic soil particles is improved by the MD replacement. The MD has a relatively low LA abrasion of 11.3% compared to the lateritic soil with LA equal to 58.1%. Therefore, the MD replacement improves the LA abrasion of the lateritic soil by reducing the LA abrasion value for the blends. The LA abrasion of lateritic soil decreases from 58.1% (for 0% MD replacement) to 41.1% (for 50% MD replacement). Even without the MD replacement, this lateritic soil is considered as durable for subbase and engineering fill materials based on LA abrasion requirement of <60% (DH-S, 1996).

### 3.2. Mechanical properties

The mechanical properties of compacted blends as an engineering fill material were evaluated. The modified compaction test results (Table 2 and Fig. 7) show that the blends at various MD replacement ratios exhibit bell-shaped compaction pattern, typical of traditional geo-materials (Horpibulsuk et al., 2008, 2009). The compaction characteristics of all blends were determined approximately using parabolic functions where the peak was defined as MDD and OMC. The maximum dry density (MDD) of the MD is relatively low (8.2 kN/m$^3$) compared to that of lateritic soil (21.6 kN/m$^3$), which is attributed to the lower specific gravity of MD. The MD replacement significantly reduces the MDD of blends from 21.6 kN/m$^3$ (for 0% MD replacement) to 16.0 kN/m$^3$ (for 50% MD replacement). The MDD values of the blends are between those of the lateritic soil and MD, which are 19.4 kN/m$^3$, 18.9 kN/m$^3$, 18.2 kN/m$^3$ and 17.3 kN/m$^3$ for 10%, 20%, 30% and 40% MD replacement, respectively. This significantly lower MDD, typical of a lightweight fill material, decreases the overburden on the foundation, which is an advantage over traditional pavement subbase materials. The decrease of optimum moisture content (OMC) is associated with the increase in MDD, which is typical of compacted geomaterial (Horpibulsuk et al., 2008, 2009). The OMC increases from 7.6% (for 0% MD replacement) to 14.0% (for 50 MD replacement). The OMC values are 11%, 9%, 12%, and 12.5% for 10%, 20%, 30% and 40% MD replacement, respectively. The OMC of lateritic soil is lower than that of MD and lateritic soil/MD blends because of lower water absorption of lateritic soil.

The soaked CBR values at modified Proctor energy of each blend increases with MD replacement ratio while the swelling values decrease with MD replacement ratio as shown in Table 2. The soaked CBR values at modified Proctor energy of each blend are 13.5%, 15.5%, 16.0%, 20.0% and 21.0% for 10%, 20%, 30%, 40% and 50% replacement, respectively. The swelling values at modified Proctor energy are 6.40%, 3.05%, 1.60%, 0.31%, 0.86% and 0.55% for the MD replacement ratios of 0%, 10%, 20%, 30%, 40% and 50%, respectively.

## 4. Discussion

The MD replacement technique has the advantage of reduced particle breakage of the blends due to compaction as evident from Figs. 2–6. The lateritic soil particles were broken down

**Table 2**
Physical and mechanical properties of marginal lateritic soil, MD and lateritic soil/MD blends after modified compaction test.

| Sample description | MD | Lateritic soil: MD | | | | | Lateritic soil | Remark |
|---|---|---|---|---|---|---|---|---|
| | | 50:50 | 60:40 | 70:30 | 80:20 | 90:10 | | |
| Compaction (Modified):Max Dry Density (KN/m$^3$) | 8.2 | 16.0 | 17.3 | 18.2 | 18.9 | 19.4 | 21.6 | AASHTO T180 |
| Compaction (Modified): OMC (%) | 10.0 | 14.0 | 12.5 | 12.0 | 9.0 | 11.0 | 7.60 | AASHTO T180 |
| California Bearing Ratio (Soaked 4 days) (%) | – | 21.0 | 20.0 | 16.0 | 15.5 | 13.5 | 9.3 | AASHTO T193 |
| Swell (Soaked 4 days) (%) | – | 0.31 | 0.55 | 0.86 | 1.60 | 3.05 | 6.40 | AASHTO T193 |
| $w_L$ (%) | – | 38.1 | 38.8 | 40.7 | 43.0 | 44.9 | 45.6 | AASHTO T90 |
| $w_p$ (%) | – | 27.1 | 26.4 | 24.9 | 25.3 | 25.9 | 24.6 | AASHTO T90 |
| Ip (%) | – | 11.0 | 12.4 | 15.8 | 17.7 | 19.0 | 21.0 | |
| $D_{10}$ (mm) | 0.8 | – | – | – | – | – | – | |
| $D_{30}$ (mm) | 1.75 | 0.65 | 0.85 | 0.60 | 0.65 | 0.55 | – | |
| $D_{50}$ (mm) | 2.60 | 2.75 | 3.25 | 2.75 | 3.00 | 2.90 | 2.50 | |
| $D_{60}$ (mm) | 3.20 | 4.00 | 4.50 | 4.00 | 4.50 | 4.20 | 4.00 | |
| $C_u$ | 4.0 | – | – | – | – | – | – | |
| $C_c$ | 1.2 | – | – | – | – | – | – | |
| Gravel size content (%) | 19.5 | 35.1 | 37.7 | 34.4 | 38.6 | 37.3 | 35.8 | Retained#4 |
| Sand size content (%) | 78.1 | 46.2 | 41.9 | 41.9 | 36.4 | 37.5 | 32.9 | Passed#4-Retain#200 |
| Fines size content (%) | 2.4 | 18.7 | 20.4 | 23.7 | 25.0 | 25.2 | 31.3 | Passed#200 |
| Classification-USCS | SP | SM | SM | SC | SC | SC | SC | |

significantly, particularly for particles smaller than 10 mm while the MD particle breakage is insignificant. By comparing Tables 1 and 2, it is evident that after compaction, the gravel-sized and sand-sized particles content of lateritic soil decreases while the silt-sized and clay-sized particles content increases; 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. The coarse (gravel and sand) content of MD decreases from 99.1% to 97.6% while the clay content increases from 0.9% to 2.4% after compaction. The change in coarse material content of MD is minimal because the decrease in gravel-sized particles is associated with the increase in sand-sized particles (Table 2). As such, MD replacement possibly prevents the breakage of the coarse aggregate and hence the minimal reduction of the fine content as noted by the small increase in fine content with increasing MD replacement ratio. The difference in fine content of the blends before and after compaction is 5.0%, 5.1%, 2.5%, 2.0% and 1.8% for MD replacement ratios of 10%, 20%, 30%, 40% and 50%, respectively. This implies that the higher MD replacement results in lesser particle breakage. The soil classification of the blends before and after compaction remains the same for all MD replacement except 30% MD replacement. At 30% MD replacement, the soil classification changes from SM to SC, which indicates that this replacement ratio is at the threshold limit for this replacement method.

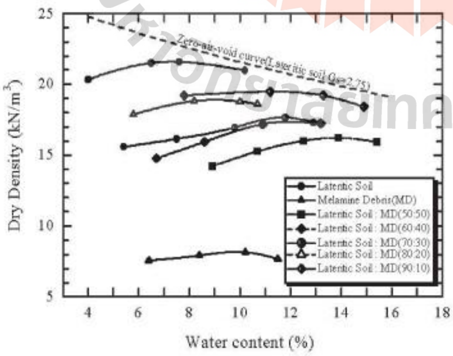



**Fig. 7.** Dry density versus moisture content relationship for various lateritic soil/MD blends.

The particle breakage leads to the increase in liquid limit and plastic limit of lateritic soil. Without MD replacement, $w_L$ increases from 40.7% to 45.6% and PI from 19.8% to 21.0% after compaction. Whereas changes in $w_L$ and $I_p$ of the blends after compaction is insignificant particularly for 50% MD replacement. Since the mechanical properties of compacted materials is governed by the after-compaction physical properties, increased particle breakage results in poorer mechanical properties. In other words, the MD replacement prevents particle breakage and hence the improvement of mechanical properties, which are soaked CBR and swelling.

Generally, bearing capacity as measured by CBR and swelling of the compacted materials are controlled by the fine content. Higher fine 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. As such, the higher MD replacement, which reduces the fine content and water holding capacity, results in the higher soaked CBR.

Even though the water absorption increases with increasing MD replacement (Table 1), the swelling of the blends decreases. In other words, the higher water absorption of the blends is not associated with the higher swelling because the MD is non-plastic and non-swelling material. Increased MD replacement increases the non-plastic material in the blends, resulting in a decrease in swelling.

Fig. 8 shows the soaked CBR values at different compaction energy levels in logarithm function. For a particular MD replacement ratio, the soaked CBR significantly increases with compaction energy, $E$. There are two linear slopes and the slope change is found at $E = 2681$ kJ/m$^3$ (modified Proctor energy). The second slope ($E > 2681$ kJ/m$^3$) is steeper than the first one ($E < 2681$ kJ/m$^3$), indicating that the compaction energy is more significant on the increase in soaked CBR when $E > 2681$ kJ/m$^3$. For a particular energy, the soaked CBR increases with the MD replacement ratio; i.e., the 50% MD replacement exhibits the highest soaked CBR for all $E$ values. It is obvious that the first slope of all the blends is essentially the same and the second slope of 50% replacement blend is the highest. This implies that the rate of soaked CBR development with MD replacement ratio at $E < 2681$ kJ/m$^3$ is essentially the same even with different MD replacement ratios.

Fig. 9 shows the swelling versus logarithm of $E$ relationship for various MD replacement ratios. Similar to the soaked CBR versus logarithm of $E$ relationship, the $E = 2681$ kJ/m$^3$ is regarded as the

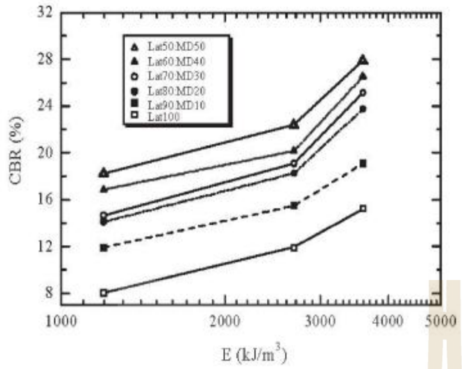



**Fig. 8.** Soaked CBR versus compaction energy relationship for lateritic soil/MD blends.

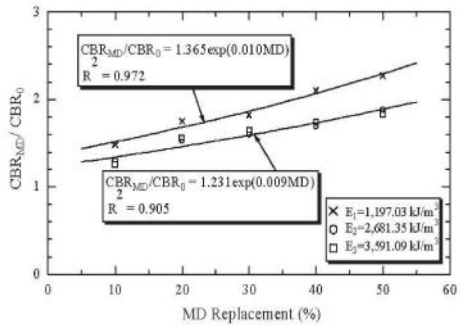



**Fig. 10.** Relationship between normalized soaked CBR and MD replacement ratio.

threshold limit separating the first and second slopes of swelling versus logarithm of $E$ relationship for lateritic soil. Without MD replacement, $E$ can reduce the swelling, especially when $E > 2681$ kJ/m$^3$ as seen that the second slope is remarkably lower than the first slope. The MD replacement significantly reduces the swelling; i.e., the swelling of lateritic soil reduces more than twice when only 10% MD is replaced. The first and second slopes of the blends are essentially the same and can be represented by a gentle linear function when MD replacement is greater 20%. It is noted that the swelling of the blends is significantly reduced even at a small $E$ level unlike the marginal lateritic soil (without MD), which requires high $E$ level to increase attractive forces among soil particles.

Based on an analysis of soaked CBR and swelling test results, it is practical to relate the soaked CBR and swelling of blends at various compaction energies in term of MD replacement. Figs. 8 and 9 show that the improvement rate of soaked CBR with MD replacement ratio is significantly dependent upon $E$ and $E = 2681$ kJ/m$^3$ is found to be the threshold limit. Whereas the improvement rate of swelling with MD replacement ratio is marginally dependent upon $E$. As such, the predictive equations (Figs. 10 and 11) for soaked CBR and swelling in term of MD replacement ratio are presented as follows:

$$\frac{CBR_{MD}}{CBR_0} = 1.365\exp(0.010MD) \quad \text{for} \quad 1197\,\text{kJ}/\text{m}^3 < E < 2681\,\text{kJ}/\text{m}^3 \tag{1}$$

$$\frac{CBR_{MD}}{CBR_0} = 1.231\exp(0.009MD) \quad \text{for} \quad 2681\,\text{kJ}/\text{m}^3 < E < 3591\,\text{kJ}/\text{m}^3 \tag{2}$$

$$\frac{S_{MD}}{S_0} = 10.867\exp(-0.06MD) \quad \text{for} \quad 2681\,\text{kJ}/\text{m}^3 < E < 3591\,\text{kJ}/\text{m}^3 \tag{3}$$

where $CBR_{MD}$ and $CBR_0$ are the soaked CBR at different MD replacement ratios (ranging from 0% to 50%) and soaked CBR at 0% MD replacement, respectively and $S_{MD}$ and $S_0$ are the swelling at different MD replacement ratios (ranging from 0% to 50%) and swelling at 0% MD replacement, respectively. These predictive equations are useful for predicting soaked CBR and swelling at different MD replacement ratios based on the values of lateritic soil (without MD replacement). The coefficients of correlation of these equations are greater than 0.91, confirming the validity of these equations. The formulation of the predictive equation is on sound principle and can be fundamental to other marginal soils.

Table 3 summarizes the physical and mechanical properties of the blends at various MD replacement ratios compared with the requirements for subbase and engineering fill materials specified by the Department of Highways, Thailand. It is evident that the

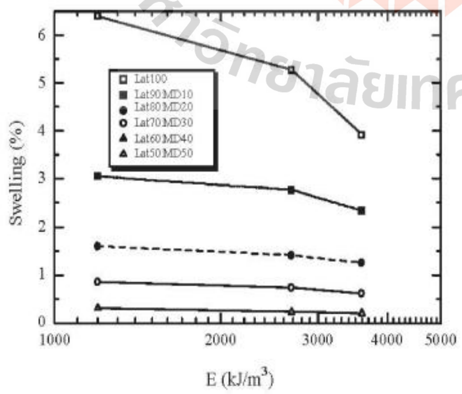



**Fig. 9.** Swelling versus compaction energy relationship for lateritic soil/MD blends.

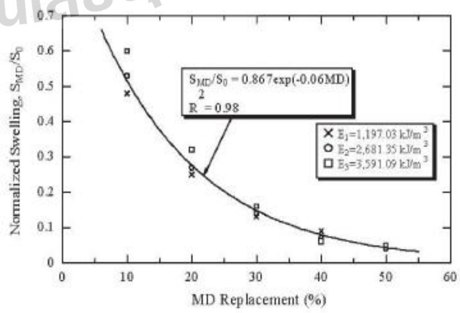



**Fig. 11.** Relationship between normalized swelling and MD replacement ratio.

**Table 3**
Mechanical properties of lateritic soil/MD blends compared with requirements for engineering fill and subbase materials.

| Sample description | Subbase material (DH-S205/2532) | Engineering fill material (DH-S208/2532) | MD | Lateritic soil: MD | | | | | Lateritic soil |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 50:50 | 60:40 | 70:30 | 80:20 | 90:10 | |
| LA abrasion value (%) | <60 | <60 | 11.3 | 41.1 | 43.3 | 47.6 | 50.4 | 51.4 | 58.1 |
| California Bearing Ratio (%) | >25 | >10 | – | 21.0 | 20.0 | 16.0 | 15.5 | 13.5 | 9.3* |
| Swell (%) | <4 | <3 | – | 0.31 | 0.55 | 0.86 | 1.60 | 3.05* | 6.40* |
| $w_L$ (%) | <35 | <40 | – | 37.8 | 38.4 | 38.9 | 39.8 | 39.9 | 40.7* |
| $I_p$ (%) | <11 | <20 | – | 11.1 | 12.6 | 15.1 | 16.6 | 17.0 | 19.8 |
| Remark | | | – | Meet to Selection Material | | | | *Not meet. | |

marginal lateritic soil has lower soaked CBR and higher swelling and $w_L$ than the requirements for both subbase and engineering fill materials. MD replacement can improve these unfavorable requirements. With 20% MD replacement, the physical and mechanical properties of blends meet the requirement for engineering fill material. The 50% MD replacement blend is also at the borderline of the specification for subbase material.

## 5. Conclusions

The marginal lateritic soil improvement by MD replacement is found to be a sustainable engineering fill material based on this research. The laboratory evaluation of the lateritic soil/MD blends at different MD replacement ratios included physical property tests such as particle size distribution, Atterberg limits and LA abrasion, as well as mechanical property tests such as soaked CBR and swelling.

MD replacement reduces plasticity, unit weight and particle breakage of lateritic soil, resulting in the improvement of both physical and mechanical properties of marginal lateritic soil. The higher particle breakage resistance minimizes the fine content after compaction; hence, the soaked CBR increases and swelling decreases with increasing MD replacement ratio. With the lower unit weight and better mechanical properties, the lateritic soil/MD blends provide lower overburden of the pavement structure on foundation and higher stability than the conventional fill materials.

The compaction energy, $E$ affects the rate of soaked CBR development with MD replacement ratio whereas the $E$ insignificantly affects the rate of swelling reduction with MD replacement ratio. As such, two predictive equations for soaked CBR in term of MD replacement ratio are proposed for $E < 2681$ kJ/m$^3$ and $E > 2681$ kJ/m$^3$, respectively while a unique predictive equation for swelling in term of MD replacement is proposed for various $E$ values. The predictive equations for soaked CBR and swelling proposed are useful for geotechnical and pavement practitioners. The soaked CBR and swelling of blends at various MD replacement ratios and $E$ values can be predicted once the soaked CBR and swelling of lateritic soil (without MD) are known. The formulation of the proposed equations is based on sound principles and can be potentially extended to other types of marginal soils.

MD replacement can improve the mechanical property requirement for engineering fill material according to national local authority. The MD traditionally destined for landfill can be used as a replacement material to stabilize lateritic soil for developing the sustainable engineering fill material. With 20% MD replacement, the physical and mechanical properties of blends meet the requirement. The 50% MD replacement blend is at the borderline of the specification for subbase material.

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