IMPROVEMENT OF COMPACTED SOIL-CEMENT USING NATURAL RUBBER LATEX FOR PAVEMENT APPLICATIONS

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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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วิทยานิพนธ์ฉบับนี้มีจุดประสงค์เพื่อศึกษาความเป็นไปได้ของการประยุกต์ใช้ดินซีเมนต์บดอัดปรับปรุงคุณสมบัติทางวิศวกรรมด้วยน้ำยางธรรมชาติ (NRL) เพื่อเป็นวัสดุชั้นพื้นทาง และรองพื้นทางในงานโครงสร้างถนน ซึ่งการใช้น้ำยางธรรมชาติมีประโยชน์อย่างยิ่งในการสนับสนุนการใช้งานวัสดุจากธรรมชาติเป็นสารผสมเพิ่มในงานด้านวิศวกรรมอย่างยั่งยืน แต่การจับตัวเป็นก้อน และความไวต่อปฏิกิริยาของปูนซีเมนต์ทำให้ดินซีเมนต์บดอัดที่ปรับปรุงด้วยน้ำยางธรรมชาติเกิดข้อด้อยซึ่งส่งผลกระทบต่อคุณสมบัติของดินซีเมนต์บดอัดในชั้นพื้นทาง โดยเฉพาะอย่างยิ่ง ในการใช้งานปูนซีเมนต์ปริมาณมาก

บทที่หนึ่งและบทที่สองจะกล่าวถึงความเป็นมาของปัญหาและจุดประสงค์หลักของงานวิจัย สรุปข้อดีและข้อเสียของการประยุกต์ใช้นำยางธรรมชาติเป็นสารผสมเพิ่มในงานวิศวกรรม รวมทั้งผลงานวิจัยในอดีตที่เกี่ยวข้องกับการปรับปรุงคุณสมบัติทางวิศวกรรมโดยการใช้น้ำยางธรรมชาติ

บทที่สามศึกษากำลังอัดและกำลังดัดของดินซีเมนต์บดอัดโดยการใช้น้ำยางธรรมชาติเป็นสารผสมเพิ่ม การการออกแบบส่วนผสมของน้ำยางธรรมชาติใช้วิธีการแทนที่ในอัตราส่วนของน้ำต่อน้ำยางธรรมชาติ ผลการทดสอบแสดงให้เห็นว่า กำลังอัดและกำลังดัดเพิ่มขึ้นเมื่อการแทนที่ของน้ำยางในอัตราส่วนเพิ่มขึ้น และพบว่าอัตราส่วนน้ำยางที่เหมาะสมทำให้ทั้งกำลังอัดและกำลังดัดมีค่าสูงสุด จากนั้นกำลังอัดและกำลังดัดลดลง โดยการเพิ่มขึ้นของน้ำยางที่เกินจุดเหมาะสม ภาพถ่ายจากกล้องจุลทรรศน์อิเล็กตรอนแบบส่องกราด (SEM) ชี้ชัดว่าแผ่นฟิล์มที่เกิดจากน้ำยาธรรมชาติเข้าแทรกตัวอยู่ในโครงสร้างของดินซีเมนต์บดอัด ช่วยเสริมความหนาแน่นและกำลัง ซึ่งช่วยเพิ่มทั้งกำลังอัดและกำลังดัด แต่ผลการวิเคราะห์มวลสารด้วยการกระจายพลังงาน (EDS) บ่งชี้ว่าปริมาณน้ำยางที่เพิ่มขึ้น ทำให้ผลิตภัณฑ์ไฮเดรชั่นลดลง

บทที่สี่ศึกษาความทนทานต่อวัฏจักรแปียกและสลับแห้ง ดินซีเมนต์บดอัดโดยการใช้น้ำยางธรรมชาติเป็นสารผสมเพิ่ม ปัจจัยที่มีอิทธิพลต่อกำลังรับแรงอัดก่อนการทดสอบการความทนทาน และกำลังรับแรงอัดหลังจากการทดสอบต่อวัฏจักรแปียกและสลับแห้ง และการสูญเสียน้ำหนัก ได้แก่ ชนิดของดิน ชนิดของน้ำยางธรรมชาติ อัตราส่วนของน้ำต่อน้ำยางธรรมชาติ และปริมาณปูนซีเมนต์ ผลการทดสอบแสดงให้เห็นว่าอัตราส่วนน้ำยางที่เหมาะสมทำให้กำลังอัดก่อน

การทดสอบการความทนทานมีค่าสูงสุด นอกจากนี้การสูญเสียน้ำหนักต่ำสุดและ กำลังรับแรงอัดหลังจากการทดสอบต่อวัฏจักรแปียกและสลับแห้งสูงสุด (w-d) ยังพบได้ในอัตราส่วนการเปลี่ยน NRL ที่เหมาะสม

บทที่ห้าศึกษาคุณสมบัติการรับแรงดึงของของดินซีเมนต์บดอัดโดยการใช้น้ำยางธรรมชาติเป็นสารผสมเพิ่ม ปัจจัยที่มีอิทธิพลต่อกำลังรับแรงอัด ความกำลังรับแรงดึงทางอ้อม และความล้าเนื่องจากแรงดึงทางอ้อม ได้แก่ ชนิดของดิน อัตราส่วนของน้ำต่อน้ำยางธรรมชาติ ปริมาณปูนซีเมนต์ และพลังงานในการบดอัดต่อ ผลการทดสอบพบว่าคุณสมบัติกังกล่าวข้างต้นเพิ่มขึ้นตามการเพิ่มของอัตราส่วนของน้ำต่อน้ำยางธรรมชาติ และค่าสูงสุดเกิดขึ้นที่อัตราส่วนน้ำยางที่เหมาะสม และยังพบว่าอัตราส่วนน้ำยางที่เหมาะสมช่วยเพิ่มความสามารถในการทนต่อการเสียรูปแบบพลาสติกที่ก่อตัวขึ้นเนื่องจากความล้าเนื่องจากแรงดึงทางอ้อม

สาขาวิชา วิศวกรรมโยธา ลายมือชื่อนักศึกษา_______________

ปีการศึกษา 2563 ลายมือชื่ออาจารย์ที่ปรึกษา_______________

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APINUN BURITATUM : IMPROVEMENT OF COMPACTED SOIL-CEMENT USING NATURAL RUBBER LATEX FOR PAVEMENT APPLICATIONS. THESIS ADVISOR : PROF. SUKSUN HORPIBULSUK, Ph.D., 178 PP.

CEMENT STABILIZED SOIL/NATURAL RUBBER LATEX/PAVEMENT

This thesis studies the possibility of using natural rubber latex (NRL) to improve engineering properties of compacted soil-cement in pavement applications. Chapters 1 and 2 present the statement of the problems and the objectives of this study, a summary of the advantages and disadvantages of using NRL as additional mixtures in civil engineering applications and the results from previous research on the improvement of engineering properties by using NRL.

Chapter 3 presents the engineering properties improvement of cement-NRL stabilized soil. The mechanical strengths were investigated via unconfined compressive strength (UCS) and flexural strength (FS) tests. The mechanical strengths improvements were examined through scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) analyses. The optimum NRL replacement ratios providing the highest density, compression, and flexural strengths were found at 20%, 15%, and 10% for 3%, 5%, and 7% cement contents, respectively. Even though the NRL films within the soil-cement matrix improved the cohesion of the soil matrix, it was found to retard cementation bonding. As such, the excessive NRL replacement not only reduced the compatibility but also retarded the cement hydration and, hence, the strength reduction.

Chapter 4 presents durability against wetting and drying (w-d) cycles of cement stabilized soil using NRL as a nontraditional additive. The effect of influence factors including soil type, NRL type, NRL replacement ratio, and cement content on the compressive strength prior to wetting and drying test (UCS_0), cyclic wetting, and drying compressive strength ($UCS_{(w-d)}$) and weight loss was examined. The highest UCS value is found at an optimum NRL replacement ratio. The lowest weight loss and highest $UCS_{(w-d)}$ are also found at the optimum NRL replacement ratio.

Chapter 5 presents the tensile properties of cement-NRL stabilized soil. The effect of influence factors including types of soil, NRL replacement ratio, water content, cement content, and compaction energy on unconfined compressive strength (UCS), indirect tensile strength (ITS), and indirect tensile fatigue life (NF) were examined. The UCS, ITS, and NF increased with increasing the NRL replacement ratio up to the highest value at the optimum NRL replacement ratio. The NRL replacement improved the capacity to withstand the developed plastic strain against fatigue.

School of Civil Engineering

Academic Year 2020

Student's Signature ____________

Advisor's Signature ____________

Co- Advisor's Signature ____________

STATEMENT OF ORIGINALITY

This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

Signed……………………

Apinun Buritatum

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Five years ago, the author has entered the School of Civil Engineering, Suranaree University of Technology, to pursue his Master's and Ph.D. degrees. It was his great opportunity to work under the supervision of Professor Dr. Suksun Horpibulsuk during master and Ph.D. Studies. The author would like to express his deepest sincere and gratitude to Professor Dr. Suksun Horpibulsuk for his guidance valuable advices, endless kindness, encouragement and enthusiasm throughout his studies. Even with his tight and hectic schedules, he always gave his time and support every time the author needed them. It has been a very pleasant experience to work under of guidance of Professor Dr. Suksun Horpibulsuk, who has highly disciplined life style, leadership character and philosophical thoughts.

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SYMBOLS AND ABBREVIATIONS

NRL	=	Natural Rubber Latex
SEM	=	Scanning Electron Microscope
EDS	=	Energy Dispersive X-ray Spectroscopy
C-S-H	=	Calcium-Silicate-Hydrate
CH	=	Calcium Hydroxide
UCS	=	Unconfined Compressive Strength
FS	=	Flexural Strength
CBR	=	California bearing ratio
USCS	=	Unified Soil Classification System
MDD	=	Maximum dry density
OMC	=	Optimum moisture content
OLC	=	Optimum liquid content
w-d	=	Wetting and drying cycles
UCS_0	=	Cyclic wetting and drying unconfined compressive strength
$UCS_{(w\text{-}d)}$	=	Unconfined compressive strength prior to w-d cycles
ITS	=	Indirect tensile strength
ITF	=	Indirect tensile fatigue
NF	=	Fatigue life
ε_p	=	Tensile plastic strain at zone 2 at the center of the sample

CHAPTER I

INTRODUCTION

1.1 Statement of the problem

The pavement structures, which are base and subbase layers, typically constructed from the granular material whose geotechnical properties the requirement for the materials selection standard. The inadequate properties, such as low bearing capacity, susceptibility to moisture, and environmental conditions, are usually found in the local material, which results in substantial pavement distress and shortening of pavement life. The use of quality materials is necessarily transported from the faraway source, causing the optional increase in the construction cost (Baghinil et al. 2014).

In order to improve the certain properties of the marginal soil for an intended engineering purpose, a soil stabilization technique is then proposed including physical, chemical, biological, or combination methods (Fang 1991), in which the different soils require different improvements on the basis of mechanical strength and resistance to the environment (Perloff and Baron 1976, Naeini et al. 2012).

Chemical stabilization is the process of the blending of soil material with the chemical admixtures of powder, slurry, or liquid to achieve the engineering purpose in the aspect of volume stability, strength and stress-strain behavior, permeability, and durability. Normally, the chemical stabilizers are divided into 2 major categories, which are traditional and nontraditional soil stabilizers (Estabragh et al. 2010).

The traditional stabilizing agents are often known as materials in the group of lime, fly-ash, and cement, which are widely popular for geotechnical engineering applications in order to suppress the swelling properties and increase the mechanical strength of soils (Rao et al. 2001, Yong and Ouhadi 2007). The certain admixtures generally consist of calcium that flocculated clay by balancing the electrostatic charges of the particles and reducing the intraparticle, leading to engineering properties development including higher strength, lower plasticity, increased workability, and alleviated swelling pressure (Little 1995 and Lin et al. 2007, Langroudi and Yasrobi 2009).

Cement stabilized soil is the most popular in the engineering pavement regarding the mechanical property's improvement due to the hardening of the cement. The cement hydration is the main stabilization mechanism of strength and engineering properties improvements as the cement hydrates. The main factors influence the properties and characteristics of cement stabilized soil including the type of soil, the proportion of cement in the mix, the moisture conditions, and the degree of compaction (Moore, Kennedy et al. 1970). The soil–cement technique has been used successfully The efficiency of cement stabilized soil has been manifested in pavement construction, channel linings, slope protection, the base layer of shallow foundations, and preventing sand liquefaction (Consoli, Prietto et al. 1998, Porbaha, Tanaka et al. 1998). Although cement stabilized material has a high-compressive strength, whereas often exhibits brittle behavior under both flexural and compressive stress, which leads to macrocracks and microcracks in road structure and pavement (Sukontasukkul and Jamsawang 2012).

Nontraditional additives have been recently adopted to improve the engineering properties of marginal soils and have been found to improve shortcomings of cement-stabilized soil. Synthetic polymer additives, such as polyvinyl alcohol and styrene–butadiene copolymer latex, have been widely used in the soil-cement stabilization. The elastic property of cement-stabilized soil can be enhanced by the inclusion of polymers because they modify the porous structures by infiltration of the nano-composite. Moreover, the interparticle bonding strength is enhanced by the polymerization of the nano-filler, resulting in the increase in both compressive and flexural strengths, durability, and the ductility of cement-stabilized soil (Tingle et al. 2007). Several laboratory experiments confirmed the significant improvement of ductility in soil-cement by using polymer additives (Tingle and Santoni 2003,Santoni et al. 2002, Newman et al. 2005, Santoni et al. 2002, and Tingle et al. 2007).

Likewise, natural rubber latex (NRL), a plant product from Hevea brasiliensis with the high tensile and impact strengths and high elastic and elongation properties (Sanhawong et al. 2017), can be used as an environmental-friendly additive alternative to synthetic polymers. Since 1880 NRL became a constitutes for using as the raw materials applying in various applications. The main composition of NRL primarily consists of cis-polyisoprene with a solid content of approximately 94% rubber hydrocarbon and 6% non-rubber substance, which is lipids and proteins carbohydrates, etc. The presence of these non-rubber compounds causes seriously undesirable characteristics on the NRL properties. Consequently, NRL has been suggested to treat with chemical additives such as ammonia to transform interfacial proteins and lipids to become negatively charged. However, ammonia can easily evaporate with the reaction to cement hydration, hence not suitable for pavement engineering application. The deproteinization method has been introduced as an effective process to eliminate the bonding of non-rubber constituents of NRL by using surfactant dodecyl sulphate (SDS) as a chemical agent. The bonding of lipids and proteins carbohydrates is destroyed and becomes water-soluble. SDS substance then covered and replaced the non-rubber layer to prevent the coagulation and improve workability (Muhammad et al. 2012, Vo and Plank 2018).

The previous research works have been reported the potentials of NRL on civil engineering application. The dominant feature of NRL can enhance the viscosity and elastic properties of the asphalt (Wen et al. 2017). Moreover, the compressive and tensile strengths of cement material, including the thermal resistance, can effectively be improved by NRL, resulting in the enhancement of ductility and strain capacity before failure. This is because the NRL film formation within the cementitious matrix serves as a nano-reinforcement. However, excessive NRL content causes an undesirable effect on the hydration in cement and concrete due to the cement retardation, causing a decrease in strength (Nagaraj et al. 1988, Muhammad et al. 2011, Muhammad et al. 2012, Muhammad and Ismail 2012, Vo and Plank 2018).

In addition, Thailand had the most natural rubber export of approximately 38.82% of the world rubber market (Thailand Rubber Authority, 2019). The combined utilization of NRL and cement can be considered as sustainable innovation to enhance the properties of cement stabilized soil. To the best of the authors' knowledge, there has been no research undertaken to date on the application of NRL on cement stabilized soil to improve the mechanical and engineering properties for the pavement application.

Since repetitive vehicle loading typically generates vertical and horizontal stresses, thereafter, the bottom half of the pavement structure occurs the tensile and flexural stresses. The insufficient flexural strength of cement stabilized materials probably leads to cracking failure such as transverse cracking. The durability against wetting and drying cycles is considered as long-term stability under extreme climate change in order to assess the performance of pavement structure. According to ASTM D559, the stability of cement stabilized soil under the damage action of wetting and drying cycles must be considered. Moreover, higher cement caused higher brittleness results in the reduction of tensile fatigue life, thereafter the sudden failure occurs with crack initiation.

Therefore, the purpose of this research aims to study the compressive and flexural strengths, durability against wetting-drying cycles, and cyclic tensile properties of cement-NRL stabilized soil. The outcome of this research will promote the usage of NRL as an alternative additive in cement stabilized soil in Thailand and other Southeast Asia countries.

1.2 Objectives of the study

1.2.1 To investigate the potentials of NRL on the mechanical property improvement of cement stabilized soil for pavement base/subbase applications.

1.2.2 To evaluate the potentials of NRL on durability against wetting and drying cycles of cement stabilized soil for pavement base/subbase applications.

1.2.3 To assess the tensile property of cement-NRL stabilized soil.

1.3 Organization of the dissertation

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

Chapter I presents the introduction part, describing the statement of the problems, the objectives of the study and the organization of the dissertation.

Chapter II presents the literature review of soil stabilization, cement stabilized soil application, characteristic and properties of Natural Rubber Latex (NRL), and influences of NRL on mechanical properties in civil engineering applications.

Chapter III presents the possibility of using NRL is an additive for stabilizing cement stabilized soil for pavement base/subbase applications. The component of NRL was investigated to explain the influences of NRL content on the stabilization mechanisms. Compressive and Flexural Strengths are used as an indicator for this investigation. The microstructural and chemical component of cement-NRL stabilized soil is observed through Scanning Electron Microscope (SEM) and Energy dispersive X-ray spectroscopy (EDS) analysis for understanding the role of influential factors controlling the strength development.

The influential factors studied in this study included water to NRL replacement ratios and cement content. The water to NRL ratios was prepared in five replacement ratios with respect to the total weight of soil-cement weight, viz. 100:00, 90:10, 85:15, 80:20, 75:25, and 70:30 respectively, and three different cement contents with respect to the total weight of soil including 3%, 5%, and 7% were studied. Compressive and Flexural Strength analysis on the compacted soil-cement samples were undertaken after 7 days of curing time.

Chapter IV presents the role of NRL on the durability of cement stabilized soil against wetting and drying durability for pavement base/subbase applications. The effect of influence factors including soil type (low and high fines content), NRL type (30%, 40%, and 50% dry rubber contents), NRL replacement ratio (10%, 15%, 20%, 25%, and 30% by weight of water), and cement content (3%, 5%, and 7% by total weight of dry soil) on the compressive strength prior to wetting and drying test (UCS_0), cyclic wetting and drying compressive strength ($UCS_{(w-d)}$) and weight loss was examined. The equation of predicting $UCS_{(w-d)}$ at various w-d cycles was proposed for various influence factors based on the critical analysis of test results. In addition, the carbon footprint assessment evaluates to study the impact of cement-NRL stabilized soil on the environment compared to cement stabilized soil.

Chapter V presents the potentials of NRL on the tensile properties of cement stabilized soil for the application of the unpaved road. The effect of influence factors including 3 types of soil (GW-GC, GP-GC, and GC), NRL replacement ratio, water content, cement content, and compaction energy on unconfined compressive strength (UCS), indirect tensile strength (ITS), and indirect tensile fatigue life (NF) was examined. Portland cement (Type I) contents were varied at 3%, 5%, and 7% by weight of dry soil, and the NRL replacement ratios were varied at 10%, 15%, 20%, 25%, and 30% by weight of water. The predictive equation of ITS by using UCS was proposed for various influence factors based on the critical analysis of test results. The CO_2-e emission values for cement-NRL stabilized soil is assessed compared to cement stabilized soil at the same target ITS.

Chapter VI concludes the present work and suggests the topic for further study.

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CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Traditional pavement structures normally construct from the high-quality materials to meet an engineering purpose in accordance with the construction standard. The material shortage then become a problem in pavement engineering. This problem subsequently led to increased construction costs due to the materials transportations from far away region. The soil stabilization consequently proposed for the purpose of local soil improvement and can be used as the pavement material (Sariosseiri and Muhunthan 2009).

2.2 Soil Stabilizations

Soil stabilization is usually related to physical and mechanical improvement to achieve some desired objective. Various processes for soil stabilizations have been suggested for different targets, which can be divided to be the main categories as physical, mechanical, and chemical stabilization (Baghini et al. 2014).

Physical stabilization usually concerns with the improvement of the physical condition such as heating and freezing. Mechanical stabilization is the process regarding engineering properties enhancement by means of the application of mechanical forces.

Chemical stabilization is the process relating to the use of chemical reaction method of additives in order to improve the stability of the soil that can be categorized to be two broad categories as traditional and nontraditional additives. Traditional stabilizers are the use of a chemical agent such as cement, lime, fly ash, and bituminous products that have been researched for a decade, and their mechanisms stabilization have been accepted and proofed from many researchers. Non-traditional stabilizers, which are diverse in their chemical ingredient, are novel innovation of a variety of chemical agents for the pavement engineering regarding the interaction with soil materials (Tingle et al. 2004).

In addition to the physical and mechanical soil stabilization, renewable technologies such as enzymes, surfactants, biopolymers, synthetic polymers, co-polymer-based products, cross-linking styrene-acrylic polymers, tree resins, ionic stabilizers, fiber reinforcement, calcium chloride, calcite, sodium chloride, magnesium chloride and more have become the alternative additive for soil stabilization. Regarding the concept of environmental material, many green products have been researched novel approaches rely upon merely lubricating and realigning the soil (Tingle et al. 2007).

The deep mixing method is also considered as the soil stabilization. The process of non-destructive and effective for deep mixing can improve the load-bearing capacity of soft or loose soil strata. The penny-sized injection probe and minimizes debris normally used for the stabilization process. The load-bearing capacity of the weak soil layer then improved to be able for the carrying designed construction load.

2.3 Factors Affecting the Strength of Stabilized Soil

The presence of the composition of organic sulfates, sulfides, and carbon dioxide contributed to undesirable factor affecting stabilized materials (Sherwood 1993).

2.3.1 Organic Matter

In many cases, the top layers of most soil constitute large amount of organic matters. The composition of organic matters often appeared on the surface layer of most soil constitute. In cases of well-drained soils, organic matters probably can distribute to a depth of 1.5 meters. The existence of organic matters usually causes the problem of the chemical reaction of soil stabilizers. For example, the problems with the hydration process of cement stabilized soil e.g. calcium hydroxide causes low pH value resulting from the retardation of the cement reaction process, hence the stabilization process cannot reach the desired objective (Sherwood 1993).

2.3.2 Sulfides

The sulfides, which in the presence of calcium carbonate, are produced from the oxidation of iron pyrites (FeS_2) on account of many waste materials and industrial products. This oxidation leads to the reaction of hydrated calcium sulfate affecting the stabilization mechanism in accordance with the reactions (i) and (ii) below

i. $2FeS_2 + 2H_2O + 7O_2 = 2FeSO_4 + 2H_2SO_4$

ii. $CaCO_3 + H_2SO_4 + H_2O = CaSO_4.2H_2O + CO_2$

2.3.3 Compaction

In several cases of pavement engineering, the impact of binder on compacted soil density is considered as an important factor. Some of the additive types provide either lower or higher compacted dry density than that un-stabilized soil at the same degree of compaction, which depends upon the additive properties (Sherwood 1993).

For cement stabilized soil, the stabilization mechanism is a hydration process taking place immediately as the cement reacts with the mixed water. The hydration mechanism essentially involves the hardening of soil-cement materials therefore it leads to a necessary to compact the mixed soil-cement as soon as possible. The belated compaction could result in undesired harden during the compaction process. Hence, extra compaction energy required in order to achieve the aimed density. This caused a seriously effect with regard to bonding breakage and then strength loss. Especially for clay, the alteration impact as mentioned above rather affects more than the other soils due to its plasticity properties effect (Sherwood 1993).

In contrast, the delayed compaction effect causes some advantages for lime stabilization. For lime stabilized soil, the fermented period necessary required in order to diffuse the reaction throughout the soil particles to balancing on clays plasticity. Subsequently, lime stabilized soil could be remixed to obtain its final compaction, thereafter it presents remarkable strength than otherwise process concerning lime stabilized soil (Sherwood 1993).

2.3.4 Water Content

Sufficient water content is essential not only for efficient compacted density but also for the stabilized reaction mechanism for the binder additive. For instance, the full hydration process for cement stabilization takes up about 20% of its own weight of water meanwhile, lime takes up about 32% of its own weight of water from the surrounding. The inadequate water content thereby causes a vie for water content between binders with soil then results in an incomplete stabilized mechanism (Roger et al. 1993; Sherwood 1993).

2.3.5 Temperature

The temperature is the primary catalyst for some type of binder such as pozzolanic reaction. The low temperature could delay the reaction between binders and soil particles, and then the strength of stabilized material decreased (Sherwood 1993; Maher et al 1994).

2.3.6 Freeze-Thaw and Dry-Wet Effect

The deterioration factors as freeze-thaw and wet-dry cycles seriously impact on the service life of pavement structure. Shrinkage and expansion forces are the major damage factor of stabilized soil, wherewith the degree of deterioration on freeze-thaw and wet-dry cycles depends upon the chemical reactions of the binder. For instance, the cement stabilized soil is susceptible to collapse dry-wet cycles due to the tension surface cracking (Sherwood 1993 and Maher et al. 2003).

2.4 Traditional Stabilizing Agents

The traditional stabilizers composed of hydraulic and non-hydraulic materials, which cause pozzolanic or hydration reactions with water, resulting in the hardened material. The most know traditional binders are cement, lime, fly ash, and blast furnace slag.

2.4.1 Lime

Lime stabilization is known for being economical soil improvement. The stabilization mechanism provides in term of an increased strength by cation exchange capacity. The transformation natural clay particle, as it flocculates, converts a clay mass into interlocking structures characterizing needle-like. Then the clays minerals change to the dried phase together with less moisture sensitivity (Roger et al. 1993).

The mechanism of lime stabilized soil could lead to a pozzolanic reaction in which pozzolana materials react with lime, causing cementitious compounds (Sherwood 1993 and EuroSoilStab 2002). This behavior can be occurred by both quicklime, CaO and hydrated lime, Ca (OH)2 and also for slurry lime for a dried soils conditions, which required water to achieve effective compaction. Quicklime is the most commonly used lime; the followings are the advantages of quicklime over hydrated lime (Rogers et al. 1996).

According to the aforementioned, quicklime immediately reacts with about 32% of water to produce the reaction. The generated heat causing by the reaction continuously causes loss of moisture due to water evaporation, resulting in an increased plastic limit (EuroSoilStab 2002; Sherwood 1993).

Sherwood (1993) revealed that the decreased plasticity caused by cation exchange in which calcium ions replace the cation from sodium and hydrogen. The addition of lime into the wet clay mineral increase pH values resulting from the soluble siliceous and aluminous compounds and then increase the ion exchange capacity. The above-mentioned compounds are reacted with calcium silica and calcium alumina hydrates, causing cementitious product. Furthermore, the pozzolanic materials comprising silica and alumina present an effectively potential to react with lime.

For many decades that lime stabilization technology has been widely applied in terms of geotechnical and pavement engineering in various application such as encapsulation of contaminants, rendering of backfill highway capping, slope stabilization, and foundation improvement. However, the restricted condition of lime stabilization is mostly involved with the presence of sulfur and organic materials, which inhibit the stabilization process and reduce strength (EuroSoilStab 2002).

2.4.2 Fly–Ash

Fly ash is a consequent by -produce from coal power plant causing by coal-fired power generation in which fly ash itself consists of little cementing properties compared to lime and cement. Fly ashes binder consequently cannot produce the desired cementing reaction on its own, however, it can react with the activator chemically to process cementitious products contributing to improving soil strength. The outstanding of fly ash usually involves cost-effectiveness and environmentally friendly. Most fly ashes have been divided into two main categories, which are class C and class F (White 2005).

The class C fly ash is manufactured by burning sub-bituminous coal having high cementing properties due to a high amount of free CaO (beyond 30%), causing self-cementing characteristics. Meanwhile, class F fly ash is generated from burning anthracite and bituminous coal, resulting in low self-cementing characteristics. Due to the limitations of free CaO available for class F fly ash, the addition of activators such as cement or lime is then required to produce a stabilized reaction. The addition of fly ashes stabilized soil causes a reduction of swell potential resulting from mechanical bonding improvement. Nevertheless, the restriction of fly ash stabilization is limit for less moisture content soil (White 2005).

2.4.3 Blast Furnace Slags

Blast Furnace Slags are the consequences of iron production by-products composing a similar chemical composition with cement materials, which is not the cement composition by itself. These slags can possess latent hydraulic properties developing by the addition of lime or alkaline material (Sherwood 1993 and Ahnberg et al. 2003).

2.4.4 Pozzolanas

The pozzolanic material usually involves siliceous and aluminous minerals that the materials itself can generate a little or no cement product. The pozzolan materials can be finely divided by the moisture content, chemically react with calcium hydroxide developing cementitious properties. The artificial pozzolan normally extracted by heat treatment of natural materials comprising pozzolanic elements such as clays, shales, and certain siliceous rocks. The by-products after the burning process then became ashes contributing to the pozzolan materials (Sherwood 1993).

2.4.5 Cement

Since 1960 the cement stabilization has widely been applied to improve the insufficient quality soil to be used as a pavement material. The cement utilization is considered as the primary and most effective stabilizing agent (Sherwood 1993 and EuroSoilStab 2002).

Portland cement composed of the main components of hydraulic calcium silicates, Tricalcium silicate, Dicalcium silicate, Tricalcium aluminate, and Tetra calcium aluminoferrite, which can react with water, causing the hardening cement product. The cement's chemical compound is presented in **Table 2.1**. The cement product from the combination of water and cement after a chemical reaction to form a solid, called cement-paste (Sherwood 1993 and EuroSoilStab 2002).

Table 2.1 the main composition of Portland cement.

Composition name	Chemical composition	initials
Tricalcium Silicate	$3CaO \cdot SiO_2$	C_3S
Dicalcium Silicate	$2CaO \cdot SiO_2$	C_2S
Tricalcium Aluminate	$3CaO \cdot Al_2O_3$	C_3A
Tetracalcium Aluminoferrite	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	C_4AF

The combination of cement pastes and aggregates such as sand and gravel, crushed stone, or other granular materials produced combined hard materials namely concrete that mostly use for the construction materials in civil engineering work. In which concrete normally consist of 7% to 15% of cement's total mass by weight.

The raw materials for manufacturing Portland cement relate to the selection of the material, crushed, ground, and proportioned, hence the cement mixture provides desired chemical and physical properties. The manufacturing of Portland cement divides into 2 main processes including wet and dry-process. For the wet-process, the suspended raw materials are prepared with sufficient water to produce the pumpable slurry materials. On the other hand, the raw materials are dried to a flowable powder for a dry-process. The manufacture of Portland cement by using dry-process has exclusively been used in the United States especially in the new plants due to its lower desired thermal energy.

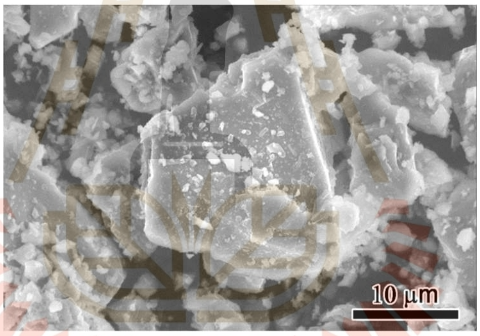

Figure 2.1 the SEM micrographs of OPC (Hongfang, 2015).

The Portland cement's major chemical component consists of calcium, silicon, aluminum, iron, and oxygen, meanwhile minor chemical constituents are generally less than 5% by weight of the mixture including magnesium, sulfur, sodium, and potassium. **Figure 2.1** presented SEM micrographs of Portland cement wherewith chemical and physical properties are summarized in **Tables 2.2**. The cementitious properties for Portland cement are consist of calcium silicates, C3S, and C2S as a strength development factor. The other main hydration product is calcium hydroxide reacting further with pozzolanic materials to further generate cement products (Sherwood 1993).

Tables 2.2 the physical and chemical properties of OPC (Hongfang, 2015).

Chemical Composition (%)	Value
SiO_2	22.52
Al_2O_3	5.80
Fe_2O_3	3.52
SO_3	2.54
Cao	62.08
Mgo	1.55
Na_2O	0.05
K_2O	0.56
LOI	0.94
Specific Gravity	3.12

For the use of cement to stabilize soil, the principal key to improving soil stability usually depends upon the cement reaction with water. The various cement type such as Portland cement, blast furnace cement, sulfate resistant cement, and high alumina cement can easily be procured in the available market. Hence the cement stabilized material is employed to improve a wide range of soils. The suitable cement type to the soil stabilization usually depends on the type of soil to be stabilized and the desired stabilization objective (EuroSoilStab 2002).

The hydration process is the immediate reaction as cement reacts with water and the other component or chemical additive to achieve the desired objective after the material harden. The cement products in the hardened state enhance the bonding strength of soil mass, whereas the physical soil structures are not changed. (EuroSoilStab 2002). The cement hydration is a time-dependent process starting from the surface of the cement grains into the center of the cement grains. They are also composed of the complex process with a complicated chemical reaction (Sherwood 1993, White 2005). The impact affecting cement hydration usually involves the presence of foreign matters or impurities, water to cement ratio, the temperature of curing, and chemical additive et cetera.

The ultimate strength and setting time of cement stabilized soil is probably vary on the involved factor, hence the mix design should take those factors into account in order to achieve the desired strength. Calcium silicates, C3S and C2S are the two main cementitious properties of ordinary Portland cement responsible for strength development (EuroSoilStab 2002). Normally the amount of cement used is small but sufficient to improve the engineering properties of the soil and further improved cation exchange of clay. For the practice, the small cement content is sufficient to improve the mechanical and engineering properties of the soil, including the cation exchange development for clay. Therefore, cement stabilization produces a consequence to reduce plasticity and volume expansion (EuroSoilStab 2002).

2.5 Nontraditional Stabilizing Agents

The definition of nontraditional soil stabilization usually related to a variety of chemical additives varying in composition and properties to react with soil material.

2.5.1 Type of nontraditional additives

Due to the commercial proprietary of each nontraditional additive, the definite composition and manufacture process is not revealed. Therefore, these stabilizer products have been grouped by like categories according to the primary chemical and objective used. There are seven categories of most of the nontraditional additive, which is ionic, enzymes, lignosulfonates, salts, petroleum resins, polymers, and tree resins. The secondary admixtures, such as surfactants, activators, and ultraviolet restraint, are usually included. The stabilization mechanism of nontraditional additives is normally supported by these complementary additives. Therefore, its mechanism consists of multiple reactions toward affecting the consequence (Tingle et al. 2007).

Ionic, lignosulfonate, salts and enzyme stabilizers have chemical mechanisms relying on the reaction with soil particles, hence its performance depends upon the soil properties. The stabilization mechanism relying on the physical process with a particle of soil such as a binder of petroleum products, tree resins, and polymers also widely improved the stability of the soil. The soil stabilizer in among of lignosulfonates, salts, and polymers could react with physicochemical mechanisms depending upon the major constituent of a used chemical (Tingle et al. 2007).

2.5.2 Ionic Stabilizers

The electrolytes or ionic stabilizers relying on the pore fluid to cause the cation exchange, causing clay minerals flocculation (Scholen 1992). The soil microstructures are altered by the mechanism of ion absorption, ionic reactions, and ion exchange, causing the reduction of soil surface charge. This process results in the loss of double-layer water, and then soil particles move to a close packing state. This stabilization mechanism would be particularly for clay because the double-layer water plays an important role in the particle sheets. Phenomenon such as the reduction in plasticity, swell potential, and particle size are the results after the completed stabilization process (Scholen 1992). Santoni et al. 2002 and Santoni et al. 2005 reported that this ionic stabilizer presented insignificant on the improvement of the granular soil. Therefore, the important purpose of ionic stabilizers is recommended only for fine-grained soils because the ion exchange affecting particles and pore fluid significantly affects behavior after the treating process. As cation exchange is required for the stabilization process, consequently, the suitability of the ionic stabilizers is depended upon the specific properties of soil. In addition, the varied chemical composition and specific reactions would occur with specific soil, hence only certain soil can be expected to good react to ionic stabilizers.

2.5.3 Enzyme Stabilizers

The enzymes are among the organic group and normally use in low concentration, which presents a specific reaction with certain soil. The conduction to the reaction for enzymes necessarily had to pore fluid to provides the means to react with the soil. In order to diffuse the enzymes to the reaction site, the curing time is required. After starting the interaction, enzymes continuously react until no more reactions to catalyze. Tingle and Santoni 2003 reported that there is only the minimum development in the wet unconfined compressive strength for low and high plastic clays for one of the enzymes. Santoni et al. 2002, Santoni and Tingle et al. 2005 reported that the granular soils not affected by the four enzyme additives for 28 days curing period. The proposed mechanism for enzyme stabilization resulting in a reduced affinity for moisture appears theoretically valid, but limited laboratory verification has occurred. Given that the proposed mechanism results in reduced affinity for water, shrink–swell tests may be appropriate for evaluating the hypothesized mechanism. Therefore, the important mechanism of enzyme stabilization is appropriate only for use with clay materials that have an affinity for pore fluid. While the as silts and granular soils are unsuitable for enzyme stabilization. In addition, the enzyme stabilization relying on the environmental and time conditions to complete the reaction. (Tingle et al. 2007).

2.5.4 Lignosulfonate Stabilizers

Lignosulfonate stabilizers are extracted from lignin of the cellulose fibers such as sodium, calcium, and ammonium lignosulfonates forming in water-soluble and susceptible to leaching under wet conditions

The chemical component of lignosulfonates varied by the plant source. The generated film of these stabilizers act as a soil particle coating and interconnecting within the soil structures. The primary purpose of the stabilization mechanism is the cementing agents, the secondary properties depending on their composition.

The cementing process is relying on the physical bonding to soil particles. Nevertheless, the lignosulfonates composed of ionic, the ion exchange process thus occurs and probably reacts only with a certain soil (Tingle et al. 2007).

Tingle and Santoni 2003 reported that the lignosulfonate stabilized CL presented a significant strength development under wet and dry UCS testing after 28 days curing period. Santoni et al. 2005 and Santoni et al. 2002 revealed that the lignosulfonate stabilized silty sand can moderately improve UCS in the wet condition compared to the un-stabilized samples. It can be implied that the stabilization mechanism of lignosulfonates is suited for granular materials. The secondary mechanism for the lignosulfonates treated granular soil is the reduction of water susceptibility, evidenced by the wet-UCS improvement (Tingle et al. 2007).

2.5.5 Salt Stabilizers

The calcium (CaCl2) and magnesium chloride (MgCl2) compounds are usually a composition of salt stabilizers. Salts serves as moisture attracting from the surrounding environment to maintain the soil and also generate the potential to exchange a cation between the divalent cations of salt and monovalent cations of the soil. The occurrence of cation exchange can reduce the space of double-layer water capacity, resulting in the close inter-particle and increases flocculation, including the soil density improvement due to the recrystallization of salts in the pore spaces (Rushing et al. 2005). In addition, salt stabilized soil also causes an increase in cohesion and strength on account of an increase in pore water surface tension.

For the coarse-grained soil, salt could be used to improve the compaction due to its hygroscopic, and then the salts recrystallization could strengthen the bonding strength between soil particles, causing strength improvement (Rushing et al. 2005). For the fine-grained soils, the hygroscopic characteristics of salts could improve the cohesive strength by the prevent soil from drying (Rushing et al. 2005). Moreover, the moderate strength improvement could be occurred by the cation exchange. Therefore, the proposed mechanism of salt stabilized soil could be suggested for both coarse and fine-grained soils. However, salts are obviously known for metal corrosion behavior and susceptible to leaching because they are water-soluble.

2.5.6 Petroleum Resins

The asphalt emulsions and synthetic isoalkane fluids represent fundamental types of petroleum stabilizers, which are typically cationic or anionic. The asphalt emulsions typically composed of asphalt particles that dispersed in an emulsifying agent. The stabilization mechanism involved with the absorption onto the soil particles. After the evaporation, the residual asphalt film coated between soil particles. The emulsified liquid serves as a surfactant to reduce the interparticle friction leading to compacted density improvement (Santoni et al. 2005).

The classification of asphalts is usually categorized in accordance with the setting time. When the medium-setting emulsions are suitable for the coarse-grained soil, meanwhile slow-setting emulsions suggested for fine-graned soil. The principle of asphalt emulsions stabilization related to the physical bonding leading to strength development, therefore, the efficiency of improvement depends upon the ability to coat the soil particles and the potential of the binder (Tingle et al. 2004).

According to the aforementioned, asphalt emulsions should be suggested to coarse-grained materials and not suitable for the fine-grained soil consists of a high specific surface area (Santoni et al. 2005). Furthermore, the application of asphalt emulsions can allow excellent waterproofing and reducing moisture susceptibility as a result of coated surface particles.

2.5.7 Polymer Stabilizers

The stabilization mechanism of polymer stabilizer related to the soil particle coating as the liquid evaporates away and then the polymer agent formed as the polymer film, resulting in the co-matrix between soil and polymer film. Similar to asphalt emulsions, the liquid of polymer can improve the compacted density by means of reducing the inter-particle friction.

The important improvement process is physical bonding enhancement. Therefore, the improvement efficiency depends on the ability to coat the soil particles as with the asphalt emulsion. (Azzam 2014). Hence, the application of this stabilization agent is suggested for granular materials and not suitable for the fine-grained soils due to its high specific area. Furthermore, the outstanding of polymer stabilization is usually involved with tensile and flexural strengths enhancement, waterproofing, and reducing susceptibility to moisture.

Rauch et al. 1993 confirmed evidence of the particle bonding mechanism by using SEM and EDS experiments. Santoni et al. 2005 reported that the polymer modified soil-cement causes improved ductility and provide early age strength. Tingle and Santoni 2003 observed that the fine-grained soil presents an insignificant strength improvement under both dry and wet tests as treated by polymer additive. Furthermore, Newman et al. 2005 have proved the toughness enhancement by using areas under the stress-strain curves of the polymer-stabilized soils compared to unmodified samples.

2.5.8 Tree Resin Stabilizers

The tree resin stabilizers are the product of the consequence of timber and paper manufacturing, improved by the emulsifying agent to prevent premature coalescence. The stabilization mechanism relying on the particle coating to enhance the physical bonding strength. As with the polymer and asphalt emulsions, tree resins are suitable for coarse grained-soil.

Santoni et al. 2002 and Santoni et al. 2005 reported that the tree resin-stabilized silty-sand soil develops strength under wet test conditions. Tingle and Santoni 2003 suggested that there is no significant effect when treating low-plasticity clay with tree resin. Tingle et al. 1999 treated the poorly graded sand with the tree resin. The result appears that the strength of modified samples is improved.

2.6 The Conclusion for Soil Stabilizers

The various soil stabilizers have an outstanding point in each category. Which some are suitable for granular materials, while some of them were suggested for use with fine-grained materials. Certain stabilizers use to reduce the plasticity, whereas some type is outstanding in strength improvement. Therefore, the utilization of soil stabilizers is necessary to determine the properties of the additive to respond to the purpose of the work application. Since this study aims to improve the quality of pavement materials and the pavement materials use in Thailand normally is the lateritic soil. Various research revealed that cement stabilization has high effectiveness for cement on the pavement materials, including lateritic soil. Moreover, the cement stabilized soil also responds the cost effectiveness and the rapid enhancement of mechanical properties, including the bearing capacity, stiffness, and strength of the soil. Consequently, this studied thereby select the cement material as the major binder.

2.7 Cement Stabilized Soil

The cement stabilization has been praised as the most effective and popular method. Since 1917 cement stabilization has been applied worldwide, including Thailand to solve the problems of quality materials shortage, afterward enormous researches have been published. The essential practice of cement stabilization is the mixtures of Portland cement with soil materials and water, then compacted to achieve the specific density under particular compaction effort energy. The cement stabilization gains strength because of the hydrate's reaction of cement reaction. Not only strength improvement, in addition, engineering properties, and durability can effectively be developed (Baghini et al. 2014).

The influences factor that controlled properties and characteristics of cement stabilized soils are consist of soil types, cement content, water content, compaction energy. Various researches have revealed the success of cement stabilization in several applications such as pavement base layers, channel linings, slope protection, shallow foundations and to prevent sand liquefaction. (Horpibulsuk et al. 2006).

Horpibulsuk et al. 2010 describes the influences of cement content on the strength development at specific water and proposed that there is a three-zone, which is active, inert, and deterioration as demonstrated in **Figure 2.2**.

In the active zone, the space and volume of small pores significantly decrease with the increased cement content due to cement product development. In the inert zone, the cement products have an insignificant effect on increasing cement, thus the strength slightly increases. In the deterioration zone, the insufficient water content results in excessive cement content, thereafter the strength decrease as increased cement content.

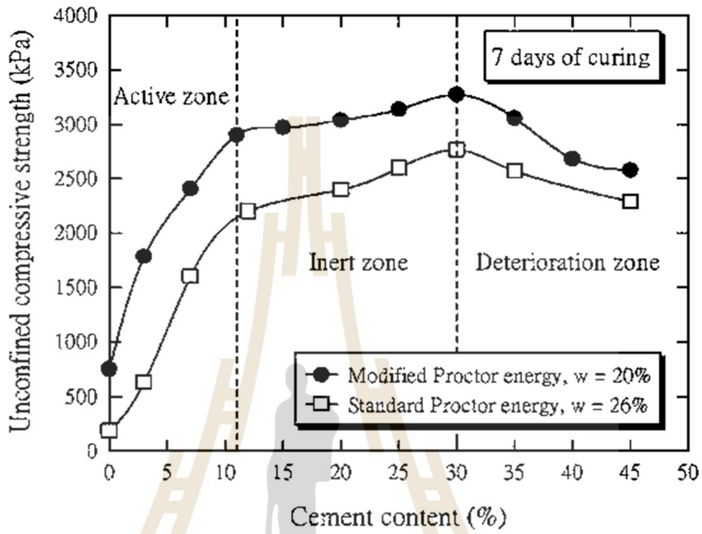

Figure 2.2 Strength developments as a function of cement content (Horpibulsuk et al. 2010)

Estabragh et al. 2010 reported that the clay soil behavior can be improved by the addition of cement with a slight change in both optimum water content and maximum dry density. The strength of clay effectively increased with incremental cement content and suggested that the strength development directly affected by the cement content and curing time.

Sariosseiri and Muhunthan 2009 found that a few amounts of cement can significantly increase the drying rate of the soil. The high effect occurs during the early state, then become the modest effect after passing half an hour. The plasticity of soil significantly increased by the addition of small cement content thereafter a higher cement dosage causes the reduction of the plasticity of the soil, leading to better workability. The optimum water content increase as the increased cement content, nevertheless it reduces the maximum dry density of the soils. Compressive strength and modulus of elasticity of soil extremely improved by the addition of cement.

The efficiency of cement stabilized low plastic soil trended to better than that of high plastic soil. Figure 2.3 illustrates the influence of cement content on the modulus of elasticity at 30% of peak axial stress for soaked and unsoaked samples. It is evident that the input cement significantly causes the modulus of elasticity improvement.

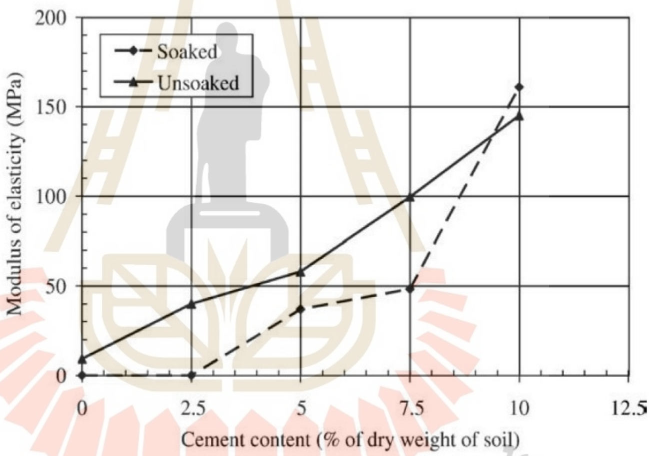

Figure 2.3 Effect of cement treatment on modulus of elasticity of Aberdeen soil (Sariosseiri and Muhunthan 2009)

Bahar et al. 2004 revealed that the higher cement content leads to the higher compressive strength of cement stabilized soil because of the development of hydration products filling within the void space. Hence, the growth of cement hydration significantly causes rigidity enhancement with the interconnection of bonding between cement product and soil particles.

Figure 2.4 demonstrates the influence of curing time on the compressive strength. It is obvious that 7-days compressive strength was 70% of the 21- and 28-days compressive strength at 10% cement content. However, the higher cement content beyond 10% needs more curing period to complete the full hydration process.

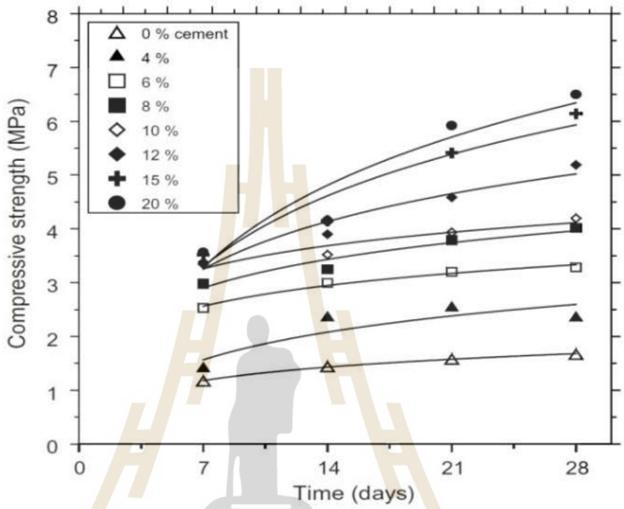

Figure 2.4 Effect of age of curing on compressive strength at different cement content (Bahar et al. 2004)

Furthermore, the slope of the stress-strain curve trend to increase with the addition of cement content. The higher slope indicates the development of the elastic modulus of the material.

Iyengar et al. 2012 reported the cement stabilized sample significantly cause the brittle failure compared to the un-stabilized sample as the curing progresses **Figs. 2.6(a and b)**.

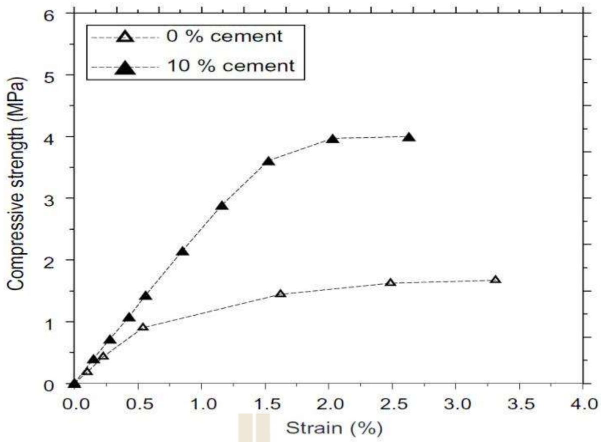

Figure 2.5 Stress-strain curves for sample under compression (Bahar et al. 2004)

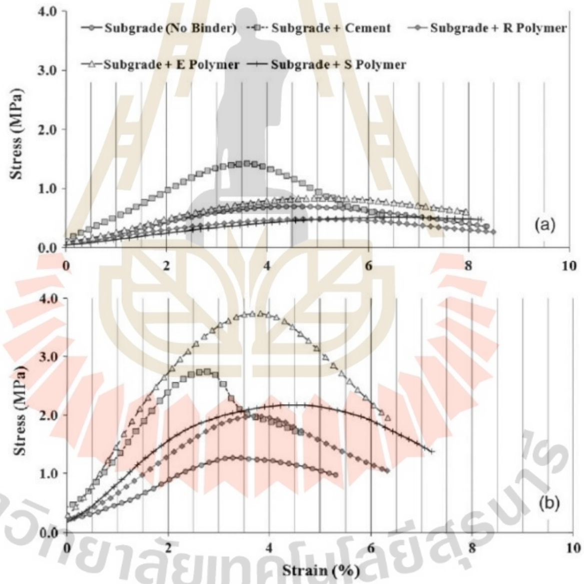

Figure 2.6 Typical stress-strain relations at (a) 1 and (b) 28 days of curing age for representative Qatar subgrade soil treated with and without various commercial binders (Iyengar et al. 2012)

2.8 Problems of Cement Stabilized Soil

In general, cement stabilization presents an excellent compressive strength. However, cement-stabilized soil, especially those with high fine contents, often exhibits brittle behavior under both flexural and compressive stress, which leads to macrocracks and microcracks in road structure and pavement.

The durability against wetting and drying are a long-term performance criterion of the pavement structure to assess the stability under number of exposures to natural disaster. Southeast Asia, including Thailand, usually suffers a variation of extreme climate, especially drought and flooding phenomena. These calamities could be considered as a serious effect on the service life of the pavement structure. In order to investigate the effect of weathering change on the damage of pavement material, the durability against wetting-drying (w-d) cycles in accordance with ASTM D559 is commonly adopted. The swelling and shrinkage upon w-d cycles accelerate the premature failure of the stabilized pavement base/subbase materials. In the drying process, the extremely decreased water content causes the suction force development until the surface tensile stress overcomes the cohesion strength of the materials, causing the crack formation. The crack formation continuously generates with the further change of moisture content until the external surface fractures exist due to irrecoverable deformation, which causes a reduction in the stability of materials. Therefore, the evaluation of service life of stabilized material via durability against w-d cycles test is significant (Biswal et al. 2019, Solanki and Zaman 2014, Yazdandoust and Yasrobi 2010, Khoury and Zaman 2002, Consoli et al. 2018, Beriha et al. 2018, Hoy et al. 2017, Suddeepong et al. 2018).

The major failure of cement stabilized soil is attributed to shrinkage crack, erosion of fine grains, and fatigue failure. The shrinkage and erosion can be overcome by using suitable materials and binders in accordance with the local and international standards of stabilized materials selection (Biswal et al. 2020). The cement stabilization effectively improved resilient modulus and the resistance to permanent deformation of the unpaved material, however, the potential of cement stabilized materials to sustain the repeated tensile loading decreases (Gnanendran and Piratheepan 2009 and Kim et al. 2012). The higher cement content caused the higher brittleness and the reduction in tensile fatigue life at a large strain level; hence, the sudden failure occurs with crack initiation.

2.9 Cement-Polymer Stabilized Soil

Synthetic polymer additives, such as polyvinyl alcohol and styrene–butadiene copolymer latex, have been widely used in the soil-cement stabilization (Thong et al. 2016; Baghini et al. 2014, 2016). The elastic property of cement-stabilized soil can be enhanced by the inclusion of polymers because they modify the porous structures by infiltration of the nano-composite. Moreover, the interparticle bonding strength between soil interparticle was enhanced by the polymerization of the nano-filler, resulting in the increase in both compressive and flexural strengths, durability, and the ductility of cement-stabilized soil (Azzam 2012, 2014; Latifi et al. 2014; Baghini et al. 2016; Mirzababaei et al. 2017; Rezaeimalek et al. 2017). The prominent features of synthetic polymer typically involve internal film formation within the microstructures of material. The flexural strength improvement is accompanied by higher elastic behavior as a result of the film formation of the polymer matrix (Yaowarat et al., 2019). Consequently, flexibility and durability are evidently enhanced by means of adhesive strength development (Baghini et al. 2014, Marto et al. 2014, Onyejekwe and Ghataora 2015, and Tingle et al. 2007). Moreover, the frequent maintenance problem of the unpaved system can be effectively solved by the participation of polymer additives. The major problems in unpaved roads such as particle loss, permanent deformation, and dust generations can also be mitigated with the utilization of an appropriated type of polymer (Steyn et al. 2014, and Starcher et al. 2018).

2.10 Natural Rubber Latex

Natural rubber latex (NRL) from the Hevea brasiliensis tree, primarily of cis-polyisoprene, is a natural material, which is outstanding in excellent physical properties. Since 1880 natural rubber latex constitutes a widely common material that is used in many aspects of the application (Kohjiya 2014) and can be used as an environmental-friendly additive alternative to synthetic polymers. In the raw state, the NRL consists of the solid and liquid composition, combined into colloidal substances. The polymer concentrations by total colloidal weight are between 25 to 40 percent. The rubber hydrocarbon was approximately 94% of total polymer solids content and 6% non-rubber components such as lipids, proteins carbohydrates (Zhao, Guan et al. 2019). Although, the non-rubber substance exists only a few amounts. These components play an important role in stabilizing the latex properties (Liyanage 1999).

The biology research revealed that the molecular structure of the NRL is comprised of 2-trans-isoprene units connecting to a long-chain cis-isoprene unit (Liyanage 1999). The latex particles of NRL was found to be in the range of 0.1–2.0 µm, which estimated from the micrographs obtained for the dip-coated film as shown in **Fig. 2.7** (Vo and Plank 2018).

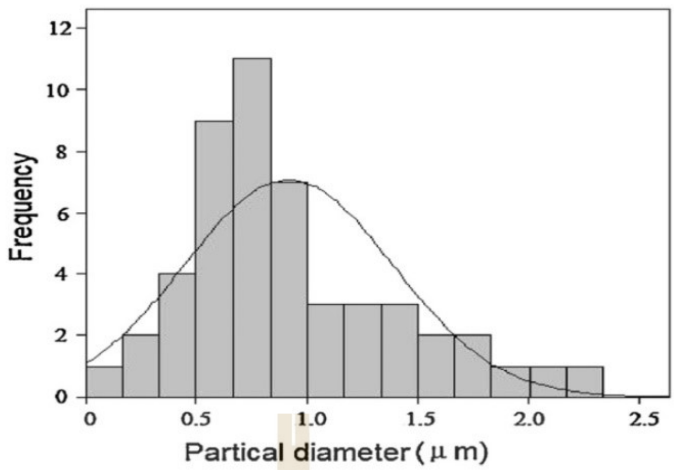

Figure 2.7 The particle size distribution of uncoalesced NR latex particles dip-coated on a glass substrate imaged one day after preparation (Nawamawat et al. 2011).

The NRL particle arrangement and agglomeration was found in the random packing that the small particle distributes between the larger particle. As the liquid drains away, the space between the particle diminishes thereafter coalescence state is achieved, causing the NRL film formation. The latex particle and the coalescence film of the NRL was demonstrated in **Figure 2.8(a-b)**. The component of the non-rubber substance such as proteins, lipids, carbohydrates, organic solutes, and inorganic substances are included in the liquid medium (Afiq and Azura 2013).

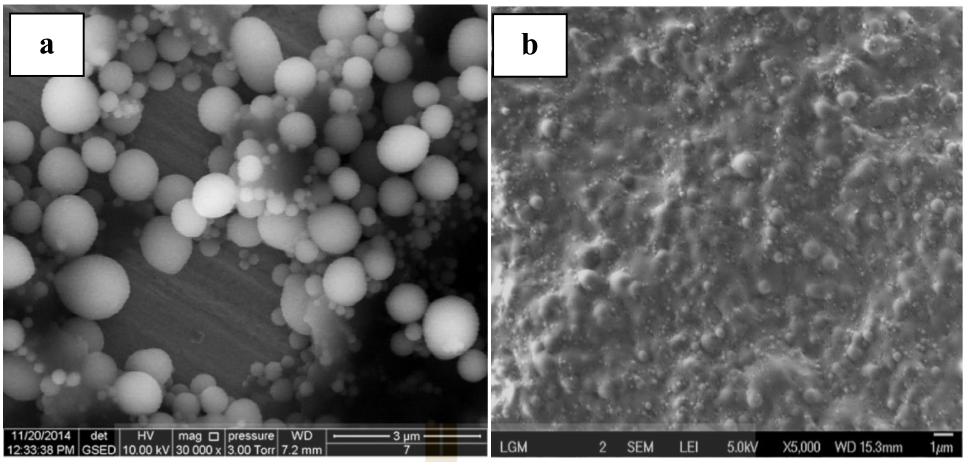

Figure 2.8 microstructures of particles packing (a) and surface morphology (b) of NRL (Norhanifah et al. 2015)

Normally, the fresh NRL is concentrated up to about 60 wt% solids content. The concentration of protein in the latex was between in the range of 1-2% of total weight, while 20-30% of protein absorbed by the latex particles (Norhanifah, Nurulhuda et al. 2015). The morphology evidence revealed that the NRL particle was spherical and surrounded by adsorbed proteins and phospholipids layers as showed in **Figure 2.9**.

For the cement and concrete application, the presence of the non-rubber components causes a negative effect on the hydration of cement. in order to mitigate this problem, the deproteinization of the NRL has been suggested by using surfactants such as sodium dodecyl sulfate (SDS) to remove the content of the protein component (Vo and Plank 2018).

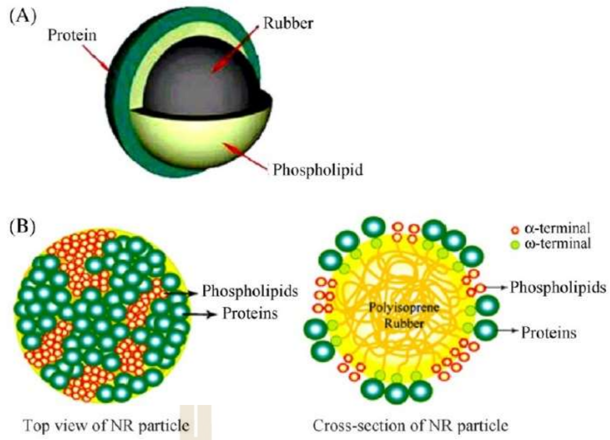

Figure 2.9 A current model of an NR latex particle surrounded by a double-layer of proteins and phospholipids (Nawamawat et al. 2011).

The surfactant is then absorbed by the protein layer leading to protein denaturation. The denaturation breaks the noncovalent that bond of protein, resulting in the destruction of their secondary and tertiary structure (Rathnayake, Ismail et al. 2012). As a result, the denatured proteins become water and water-soluble releasing in the colloidal liquid. The protein layer surrounding the NRL particle is then replaced and covered by the surfactant in order to prevent particle coagulation (Muhammad et al. 2011).

Nagaraj et al. 1988 reported that the tensile strength of concrete can be enhanced by using NRL as an admixture, moreover, the ductility of the concrete can also be improved as presented in **Figure 2.10**.

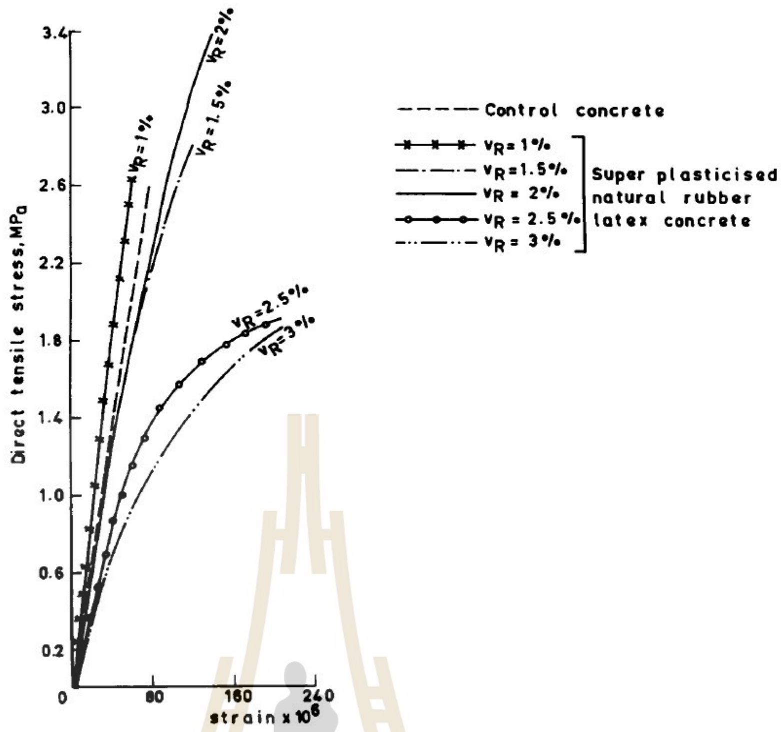

Figure 2.10 Stress-strain curves in tension of concrete with natural rubber latex (Nagaraj et al. 1988)

Muhammad et al. 2011 presented the morphological evidence of NRL modified concrete as illustrated in **Figure 2.11.** Modified mixes on the other hand, have shown more compacted features depending upon the latex contents included in the mix. The NRL modified concrete evidently presence a dense structure depending upon the latex contents included in the matrix. For instance, 10% of latex (**Figure 2.11b**) relatively have a more compacted cement matrix than that 20% of latex (**Figure 2.11c**). In fact, 20% of latex appeared completely filled-up void space, and the coalescence film is coated surface of hydration product as well as aggregate. Where the latex film emerges to be a membrane as presented in Figure **2.11d**. It can be manifested that 10% of latex presented as deeper and larger void space, have more cementitious product than that 20% of latex. Therefore, the denser characteristic by the modified NRL for 20% of latex indicate a restriction of the growth of cement hydration by blocking the moisture absorption which normally is necessary use for the chemical reaction of the concrete matrix.

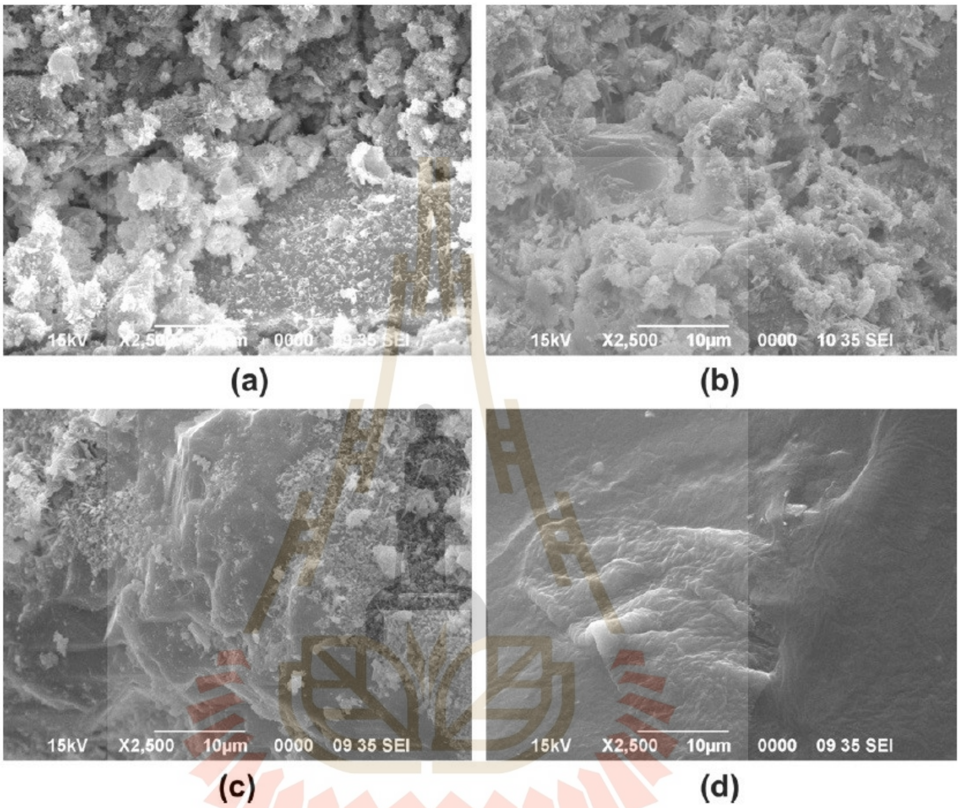

Figure 2.11 Morphologies; (a) normal cement-sand matrix, (b) cement-sand with 10% latex, (c) cement-sand with 20% latex and (d) latex-film (Muhammad et al. 2011).

Muhammad et al. 2012 studied six type of modified NRL on concrete properties. The compressive strength of concrete affected by the NRL. The compressive strength improvement was found at the small amount of latex. The lowest compressive strength has associated the sample containing the highest content of volatile, fatty acids, and metals, especially zinc are an important factor causing strength impairment as compared to un-modified concrete.

Vo and Plank 2018 studied the influences of NRL on the mortar. The results instigate that the NRL caused a decrease in the compressive strength of modified mortar. In contrast, the tensile strength of NRL modified mortar is higher than that of the unmodified sample.

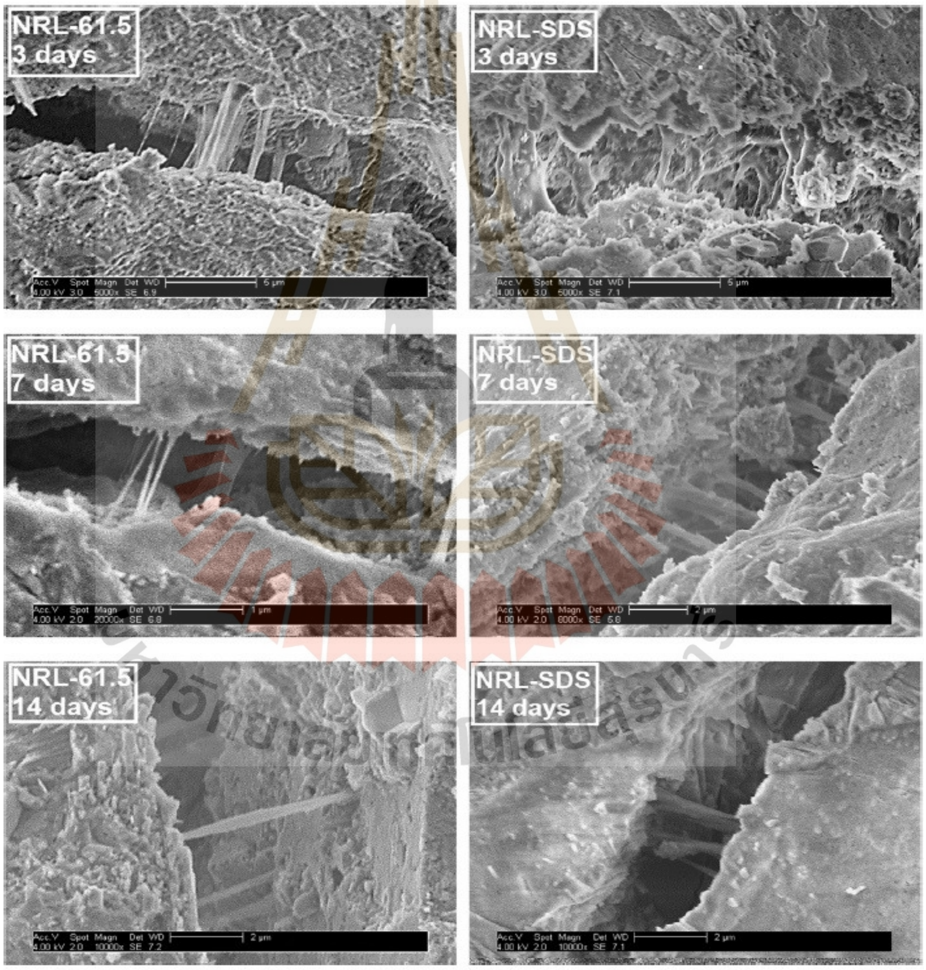

Figure 2.12 SEM images of fractured surfaces of mortar specimens containing NRL (a) and NRL–SDS (b) after 3, 7 and 14 days curing (Vo and Plank 2018).

Figure 2.12 the SEM image of mortars prepared from the NRL samples. All samples show abundant polymer films within the cementitious matrix. The films interconnect with cement hydrates and bridge the pore space. The abundant latex films within the cementitious product were detected. The latex films serve as the interconnected reinforcement between the cement product and void space. Consequently, this mechanical flexibility of mortar was then developed, resulting in the increased tensile strength.

2.11 Conclusion

Southeast Asia is the biggest natural rubber cultivation in the world. The production of rubber in this region is more than 50% of the total rubber production worldwide. The top three countries include Thailand, Indonesia, and Vietnam. According to the statistical data in 2019 of Rubber Authority of Thailand, Thailand had the most natural rubber export of approximately 38.82% of the world rubber market (Thailand Rubber Authority, 2019).

In addition to the usage of NRL in buildings, NRL can be applied in road construction. Road is the major transportation infrastructure in Asian countries including Thailand. The Thailand Office of Transport and Traffic Policy and Planning (2018) reported that the growth rate of Thailand's transportation network was more than 50%.

To the best of the authors’ knowledge, there has been no research undertaken to date on the usage of NRL in pavement geotechnics to improve the mechanical strength, durability, and tensile properties of cement stabilized base/subbase including the unpaved cement base, which is the focus of this research.

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CHAPTER III

MECHNICAL STRENGTH IMPROVEMENT OF CEMENT STABILIZED SOIL USING NATURAL RUBBER LATEX FOR PAVEMENT BASE APPLICATIONS

3.1 Statement of problem

A pavement structure is generally composed of base and sub–base layers, which play an important role in the bearing capacity and serviceability of the road. This pavement structure normally requires the appropriate soil as construction material. However, natural soil recently exhibits unfavorable physical and engineering properties, which are often not applicable for high volume road construction (Horpibulsuk et al. 2006, Sariosseiri and Muhunthan 2009, Baghini et al. 2014).

Soil improvement technique has been adopted as an alternative method for improving the deficient quality materials to achieve the criteria for pavement material selections. The technique includes physical, mechanical, and chemical methods. Chemical stabilization is extensively researched and also widely employed in pavement applications by using a single additive or combinated additives (Naeini et al., 2012, Marto et al., 2014). The stabilizers are practically divided into two main categories namely traditional and non-traditional additives (Onyejekwe and Ghataora 2015).

Traditional additives include lime, fly-ash, and cement. In general, the effectiveness and reliable performance of these substances have been extensively researched, usually related to their interaction behaviors. (Tingle et al., 2007). The utilization of Portland cement as a stabilizer has prominently conquered other additives in the traditional group in Southeast Asia due to its cost effectiveness and the rapid enchancement of mechanical properties including the bearing capacity, stiffness, and strength of soil. Its hydration gradually generates cement matrix within the void space of soil to achieve desirable strength (Tingle and Santoni 2003, Horpibulsuk, et al. 2005, Horpibulsuk, et al. 2010, Horpibulsuk, et al. 2012, Baghini et al. 2014). However, the cement stabilized soil especially wih high fine contents often exbihits brittle behavior under both flexural and compressive stress, which leads to macro- and micro-cracks in road structure and pavement (Jamsawang et al. 2014, Correia et al. 2015).

The non-traditional additives have been recently adopted to improve engineering properties of maginal soil. Some of them can improve the shortcoming of cement stabilized soil. They can modify microstructures of materials to enhance the serviceability and durability of cement stabilized soil. They include enzyme, acid, salts, resins, natural resins, and polymers (Tingle et al. 2007, Estabragh et al. 2010, Rezaeimalek et al. 2017, Mirzababaei et al., 2018).

The synthetic polymer additives such as polyvinyl alcohol, and styrene–butadiene copolymer latex has been widely used in the soil-cement stabilization. Elastic property of cement stabilized soil can be enhanced by the inclusion of polymers because they modify the porous structures by infiltration of nano-composite. The production of nano-particles can be participated into void space of cement stabilized soil. Consequently, inter-particle bonding strength between soil inter-particles was enhanced by polymerization of nano-filler, resulting in the increase in both compressive and flexural strengths, durability, and the ductility of cement stabilized soil (Azzam 2012, Azzam, 2014, Latifi et al. 2014, Baghini et al. 2016, Mirzababaei et al. 2017, Rezaeimalek et al. 2017).

Thailand is an agricultural country, which can produce and export natural rubber products in the top three ranking of the world. In order to impel the country's economy, the Thailand government has encouraged the utilization of natural rubber, starting with propelling from the industrial sector to the transportation sector. According to the statistical data of the transport infrastructure status report 2018 (Thailand Office of Transport and Traffic Policy and Planning 2018), the growth of Thailand's road transportation system from 2018 to 2019 increased more than 200,000 kilometres and is expected to increase more to support the economic growth.

Natural Rubber Latex (NRL), a suspended dispersion of *cis*-1,4-Polyisoprene, is typically polymerized from Hevea brasiliensis tree. The suspended component, the raw-state liquid, consists of approximately 94% particles of rubber hydrocarbon and 6% of non-rubber substance, which are composed of inorganic compound, sludge, acids, and protein. Based on morphology and microstructural analysis, the particle size of rubber latex is estimated to a range of 0.1 – 2.0 m. The morphological shape of NRL particle is a spherical molecular in the randomly packing state and is covered by the mixed layers of protein and phospholipids. The presence of proteins and phospholipids phases in the non-rubber components is an important factor of the coagulation and other undesired effects. However, these problems can be overcome by treating and surfactanting with the substances contianing ammonia, zinc oxide and sodium dodecyl sulfate to modify the rubber molecules to suitably apply in engineering or other works

(Sakdapipanich 2007, Nawamawat et al. 2011, Afiq and Azura 2013, Norhanifah et al. 2015).

The NRL has been researched and applied in concrete technology and mortar mixtures as a eco-friendly material (Nagaraj et al. 1988, Muhammad et al. 2011, Muhammad et al. 2012, Vo and Plank 2018). The nano-composite of NRL can form a latex film, which causes the transformation of cement matrix to be the latex cement co – matrix by the infiltration of polymer film within the porous (Muhammad and Ismail 2012, Diab et al. 2014). The utilization of NRL additives into concrete and mortar has therefore a significant effect on strength and toughness development (Nagaraj et al. 1988). Moreover, environmental resistances, acid resistance, sulphate resistance and thermal degradation, are significantly improved (Muhammad et al. 2011, Muhammad et al. 2012).

To the best of the authors' knowledge, there has been no research undertaken to date on the application of natural rubber latex to improve the engineering properties of cement stabilized soil as a pavement base material, which is the focus of this research. A series of laboratory tests were carried out to evaluate maximum dry density, optimum liquid (NRL and water), compressive strength and flexural strength. Moreover, the scanning electron microscopy (SEM) and energy dispersive x-ray spectroscopy (EDS) were employed to confirm the evidence of latex film formation and to investigate the chemical reaction within soil-cement-NRL matrix, which controls the mechanical strength improvement.

3.2 Materials

3.2.1 Soil Sample

The soil samples were a coarse-grained soil, collected from a borrow pit in Nakhon-Ratchasima Province, Thailand. The grain size distribution is illustrated in **Figure 3.1**, indicating 5.85% fine-grained particles and 94.15% coarse-grained particles in which 56.80% were gravel and 37.35% were sand. According to Unified Classification System, this soil was classified as GW-GC. Basic and engineering properties of soil are summarized in **Table 3.1** and compared with the Department of Highways standards for base and subbase materials (DH-S201/2544, DH-S205/2532). It was found that the studied soil did not achieve the minimum requirements for both base and subbase materials. However, its properties met the requirement for stabilized pavement base according to the DH-S204/2532 standard.

Table 3.1 Basic and engineering properties of soil sample

Sample Properties	Soil sample	Standard for base materials (DH-S201/2544)	Standard for sub-base materials (DH-S205/2532)	Standard for stabilization of base materials (DH-S204/2532)
	Values			
Largest particle size (mm)	25	≥ 50	≥ 50	≥ 50
Los Angeles abrasion (%)	34	≥ 40	≥ 60	≥ 60
Liquid limit LL (%)	21	≥ 25	≥ 35	≥ 40
Plastic limit PL (%)	8	≥ 6	≥ 11	-
Plasticity index PI (%)	14	≥ 6	≥ 11	≥ 15
Specific Gravity (G_s)	2.78	-	-	-
Maximum dry density (kN/m^3)	20.87	-	-	-
Optimum water content (%)	8.07	-	-	-
California bearing ratio (%)	18.16	≥ 80	≥ 25	-

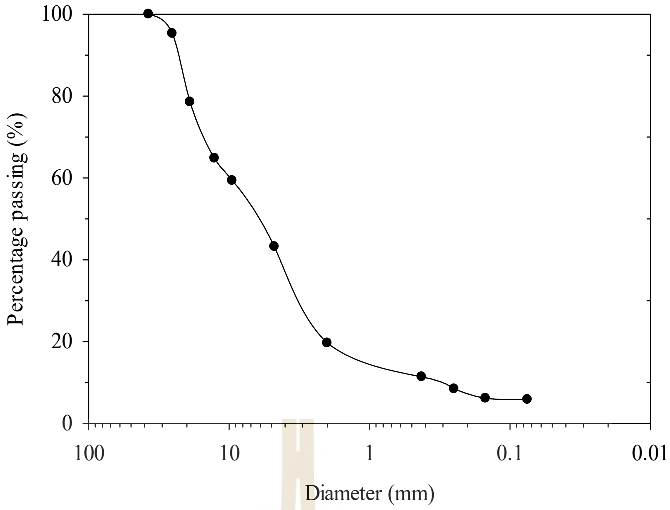

Figure 3.1 Particle size distributions of soil

3.2.2 Cement

Ordinary Portland cement was selected as a cementing agent. The chemical compositions are summarized in **Table 3.2**.

Table 3.2 Chemical Compositions of Cement

Composition	Value (%)
Silicon dioxide	20.7
Sulfur oxide	4.8
Ferric oxide	3.1
Aluminum oxide	4.4
Calcium oxide	63.3
Magnesium oxide	2.8
Loss on ignition	0.9

The initial and final setting times were 101 minutes and 188 minutes, respectively. The compressive strengths at 7 days and 28 days were 24.7 MPa and 32.6 MPa, respectively.

3.2.3 Natural Rubber Latex (NRL)

The natural rubber latex (NRL), obtained from the Rubber Authority of Thailand, was used in this research. It contained sodium dodecyl sulphate (SDS) as a surfactant to remove protien. Moreover, zinc 2-mercaptobenzothiazole (ZMBT), zinc oxide, calcium carbonate, and sulphur substance were included to improve workability and desired properties of NRL. The compositions are illustrated in **Table 3.3**. The total solid contents were 33.06 % by total weight, which included the dry rubber content of 30.79% by total weight of NRL. The studied NRL is classified as the low category, having DRC lower than 31%. (Muhammad et al. 2012).

Table 3.3 Properties of NRL

Properties	**Values**
Sludge content (%wt)	2.46
Coagulum content (%wt)	0.024
Volatile fatty acid No. (%)	0.01
Specific Gravity (G_s)	0.96
pH	8

3.3 Experimental procedures

3.3.1 Preparation and testing condition

The soil samples were sieved to remove coarser aggregates than 19 mm and air-dried (Horpibulsuk et al. 2006). Portland cement was mixed with the soil samples at various contents of 3, 5, and 7% by weight of dry soil. The soil-cement mixture was then mixed with liquid (NRL and water) at different NRL replacement ratios of 10%, 15%, 20% and 30% weight of water. In order to obtain compaction characteristics according to ASTM D1557 standard, the cement and dried soil were thoroughly mixed together for 10 minutes and then mixed with liquid at various NRL replacement ratios for other 10 minutes prior to being compacted under modified Proctor energy. The maximum dry density (MDD) and optimum liquid content (OLC) values of each mix proportion were used to prepare the cement stabilized samples for mechanical (compressive strength, and flexural strength) tests and microstructural analysis.

3.3.3 Unconfined compressive strength

Unconfined compressive strength (UCS) of unstabilized and stabilized samples was examined at different mixing ingredients to evaluate the influence of NRL on compressive strength. According to ASTM D1633 standard, the samples were prepared by using a melallic mold with dimensions of 101.60 mm diameter and 116.8 mm height. At least 3 samples were prepared by a static compression machine at MDD and OLC to ensure the density’s uniformity of the sample and the reliability of test result. The samples were removed from the mold after 24 hours and wrapped by plastic sheets. Subsequently, these compacted samples were stored in a humidity room at 25°C temperature for 7 days. The UCS tests on the 7-day samples were carried out at a compression rate of 1 mm/min by using a universal testing machine with an automatic data recorder.

3.3.4 Flexural strength

The soil-cement road base structure often exhibits the brittle behavior when subjected to the traffic load under flexural condition. The flexural strength tests on cement stabilized samples were then carried out to investigate the role of NRL on the flexural strength, which is the important factor for the pavement design. According to ASTM D1635 standard, the stabilized samples at various NRL ratios were statically compressed at MDD and OLC in a standard beam mold with dimensions of 76 mm height, 76 mm width, and 290 mm length. The samples were then demolded after 24 hours, wrapped by plastic sheets and cured for 7 days in a humidity room at 25°C temperature. The flexural tests were run using a universal testing machine at a deflection rate of 1 mm/min. The load and deflection were automatically recorded to determine the flexural strength and failure state.

3.3.4 Scanning electron microscopy and Energy dispersive X-ray spectroscopy

The morphology analysis was carried out by scanning electron microscope (SEM), which is the high efficiency system to examine the microstructures of materials. The SEM samples were collected from the fraction of the UCS sample at the middle after broken by strength testing. The small samples were immersed in liquid nitrogen at a freezing temperature of -195°C to stop cement hydration before gold coating. The 2500x magnification was selected to detect the change in morphology due to the NRL replacement randomly at least five points. The EDS analysis was employed to identify the chemical characterization of cement stabilized samples by using area mapping analysis to observe the impact of NRL on mechanical strengths.

3.4 RESULTS AND DISCUSSION

3.4.1 Compaction Characteristic

The relationship between OLC and MDD of 3%, 5% and 7% cement content at various NRL replacement ratios is summarized in **Figure 3.2**. The MDD of cement stabilized samples without NRL (water:NRL = 100:0) increases with increasing the cement content while the OLC slightly increases with increasing the cement content. This result is similar to the previous findings (Horpibulsuk et al., 2006, Sariosseiri and Muhunthan 2009 and Baghini et al. 2016)

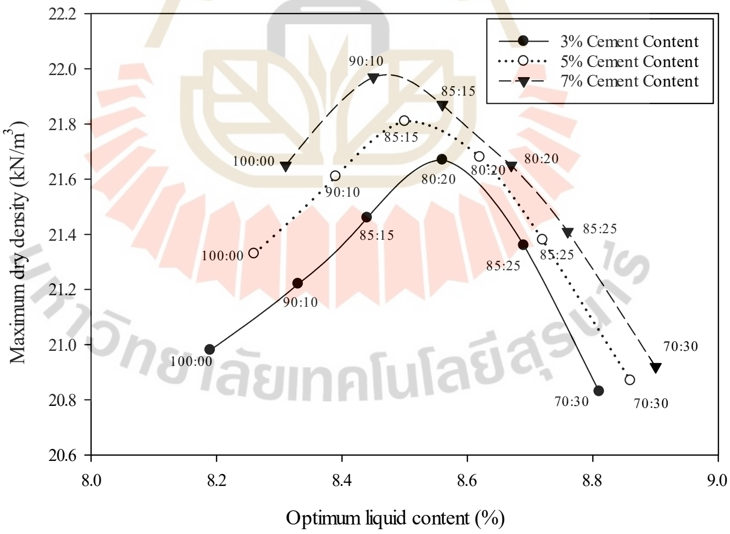

Figure 3.2 The relationship between maximum dry density and optimum liquid content.

The OLC increases gradually with increasing NRL replacement ratio for all cement contents tested as presented in **Figure 3.2**. The higher NRL replacement ratio (the lower water in total liquid) causes the higher OLC due to inadequate water for the compaction. Initially, the higher NRL replacement ratio leads to the higher MDD where the highest MDD values are found at the optimum NRL replacement ratios of 20%, 15%, and 10% for 3%, 5%, and 7% cement, respectively because the compressibility of cement stabilized soil is improved by the nano-composite of the latex. Infiltration of NRL in the soil-cement matrix causes the lubrication of inter-particles, resulting the increase in density with increasing NRL replacement ratio. Beyond the optimum NRL replacement ratio, the MDD decreases as the NRL replacement ratio increases due to the excessive solid phase of NRL within soil-cement matrix. In other words, the redundant NRL content transforms soil-cement matrix to be weak structures; the excessive NRL replacement ratio is accompanied with the increased OLC, resulting in the excessive liquid content in unit volume and the decrease in MDD. This result is similar to the previous research on cement and synthetic latex stabilized soil (Baghini et al. 2015).

The highest optimum NRL replacement ratio is found for the 3% cement, while for higher cement content (5% and 7%), the small amount of NRL replacement ratios are sufficient to fulfil the pore space. In the other words, the optimum NRL replacement ratio increases with decreasing the cement content. The NRL particles of 0.1 – 2.0 m can be more coagulated at higher cement content because the cement grains interacted with non-rubber substance (Nagaraj et al. 1988, Muhammad et al. 2012). This coagulation interrupts the lubrication of inter-particles, hence the reduction in compatibility of cement stabilized soil.

3.4.2 Unconfined Compressive Strength (UCS)

The influence of the NRL replacement ratio at various cement contents on stress-strain behavior and UCS is presented in **Figures 3.3** and 3.**4**, respectively. The cement stabilized soil obviously demonstrates brittle behavior with a small strain at failure, especially at a high cement content.

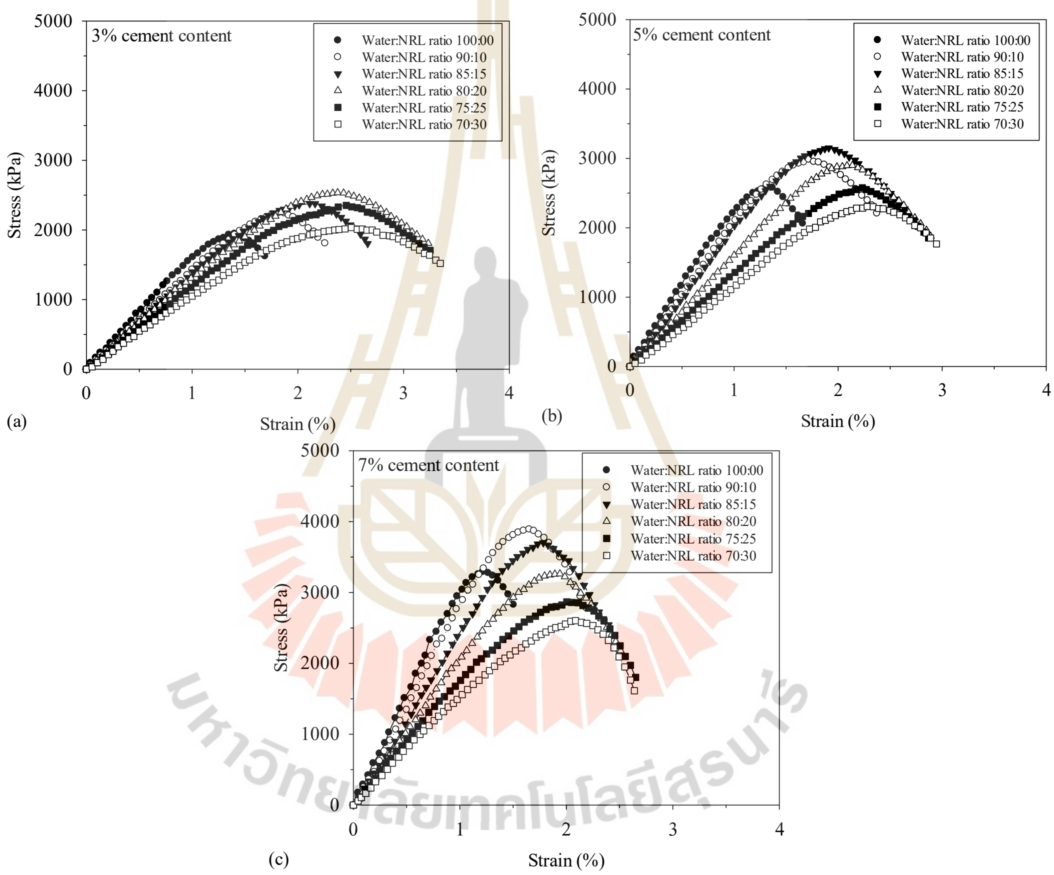

Figure 3.3 Stress-strain behavior at various replacement ratios and cement contents of (a) 3% cement; (b) 5% cement; and (c) 7% cement.

The incremental NRL replacement ratio evidently improves the ductile behavior and strain at peak strength for all cement contents (**Figures 3.3a-3.3c**). The increase of strain at peak strength improves the strain energy up to the peak strength that defined as the region under stress-strain curve (Mirzababaei et al. 2017). The increase of UCS is observed with the increase in NRL replacement ratio up to the optimum value. However, the deterioration of strength improvement is emerged by the further increase in NRL replacement ratio beyond the optimum value. The samples can sustain more stress at post-peak state due to the NRL replacement.

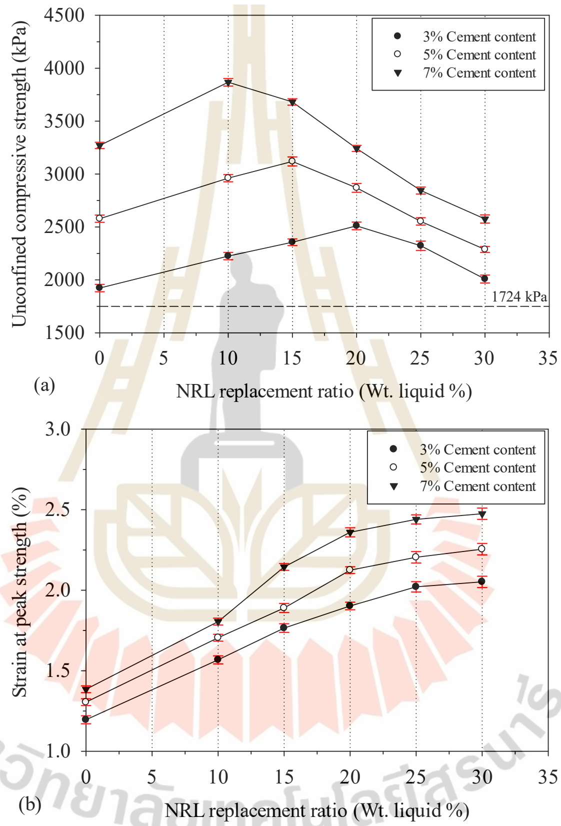

Figure 3.4 Unconfined compressive test results for different cement contents and NRL replacement ratios: (a) unconfined compressive strength; and (b) strain at peak strength.

Figure 3.4a shows the strength development with the NRL replacement ratio of cement-NRL stabilized soil at various cement contents. The dotted line in **Figure 3.4a** indicates the minimum strength requirement for cement stabilized base materials by the Department of Highways, Thailand (DH-S204/2556). For the cement stabilized samples without NRL, the UCS increases with increasing cement content (**Figure 3.4a**) because of the increased inter-particle bonding strength within the soil matrix. The increased UCS is associated with significant reduction in the strain at peak strength, showing the brittle behavior as shown in **Figure 3.4b** (Lorenzo and Bergado 2004, Horpibulsuk et al. 2010).

It is evident that the NRL replacement can enhance the UCS of cement stabilized soil. The highest UCS value is found at optimum NRL replacement ratios of 20%, 15%, and 10% for 3%, 5%, and 7% cement, respectively. At the optimum NRL replacement ratios, the UCS values are improved up to 30%, 21% and 18% higher than the UCS values when without NRL for 3%, 5%, and 7% cement, respectively. The percentage of improvement is higher for lower cement content.

3.4.3 Flexural Strength (FS)

The flexural strength (FS) tests were performed on the samples having the same mixing ingredients as the UCS tests to evaluate the role of NRL replacement on the modulus of rupture according to ASTM D1635. The test results are illustrated in **Figures 3.5** to **3.7**. The relationship between FS versus deformation for different cement contents and various NRL replacement ratios is summarized in **Figure 3.5(a-c)**. The FS development with increasing the cement content is clearly observed with the deflection-softening. The sudden failure after the peak FS is also observed for all cement contents, showing the brittle behavior.

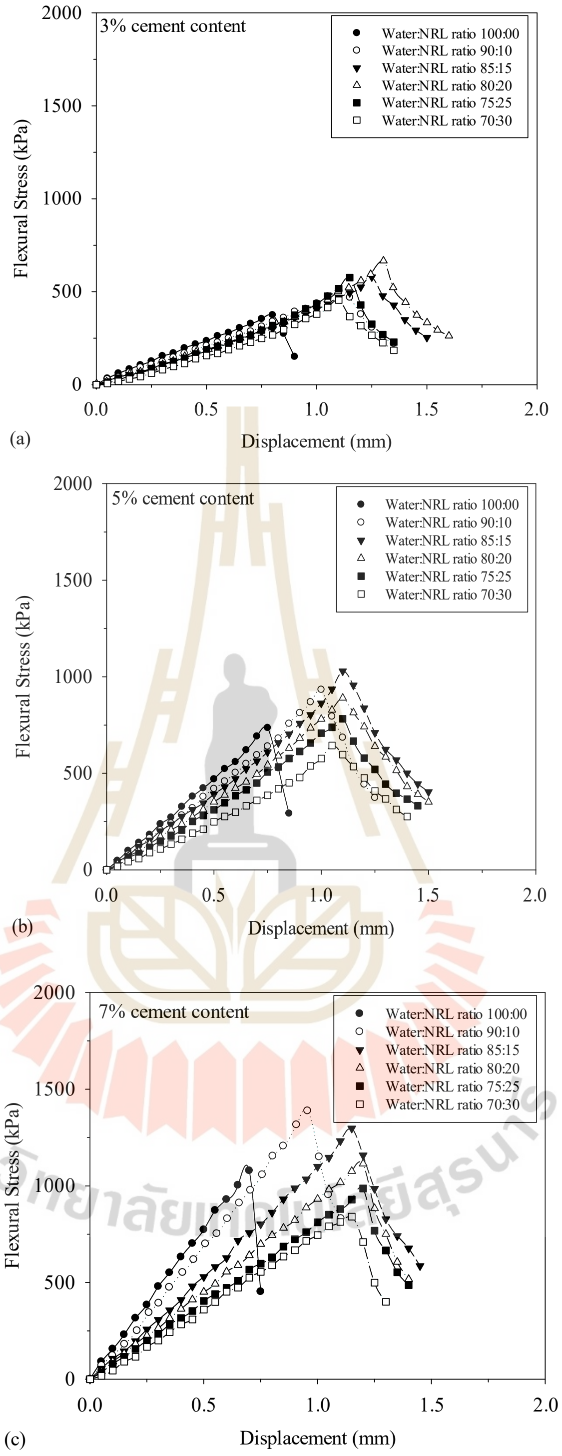

Figure 3.5 Flexural behavior at various replacement ratios and cement contents of (a) 3% cement; (b) 5% cement; and (c) 7% cement.

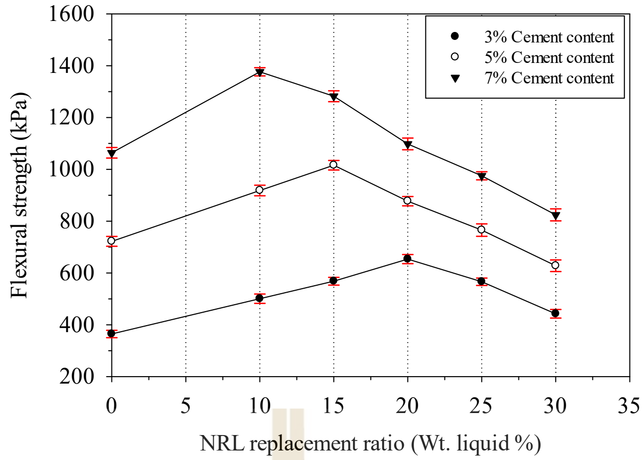

Figure 3.6 Flexural strength at different cement contents and NRL replacement ratios.

The FS and deformation at failure are higher with higher NRL replacement ratio as also shown in **Figure 3.5**. The larger deformation at failure is associated with the more region under the relationship between FS versus deformation, indicating the toughness improvement. The smaller stiffness, the gentler slope of relationship between FS versus deformation, is associated with the higher toughness. In other words, the ductility, toughness and FS are improved by the NRL replacement for all cement contents. Moreover, the NRL replacement also improves the post-peak beahvior. The NRL latex film, which is formed within soil-cement particles, can sustain higher tensile stress after the break down of the cementation bonds, hence prevent the sudden failure after peak.

It is evident that the FS can be significantly improved by the increased latex film (**Figure 3.6**). The optimum NRL replacement ratio providing the highest FS and UCS is the same for the same cement content (20%, 15% and 10% for 3%, 5% and 7% cement). Similar to UCS, the decrease of FS is found when the NRL replacement ratio exceeds the optimum value. However, the influence of NRL on the FS improvement is twice superior to that on the UCS improvement; i.e., the percentage of improvement at optimum NRC replacement ratios is found to be 78%, 40%, and 29% for 3%, 5% and 7% cement, repetitively.

Since both UCS and FS are directly related to the NRL replacement ratios, it is logical to develop a relationship between FS versus UCS as shown in **Figure 3.7** for different cement contents and NRL replacement ratios. The data points lie between two equations (FS = 1/5UCS and FS = 1/3UCS), which are suggested by ACI 230 (2009).

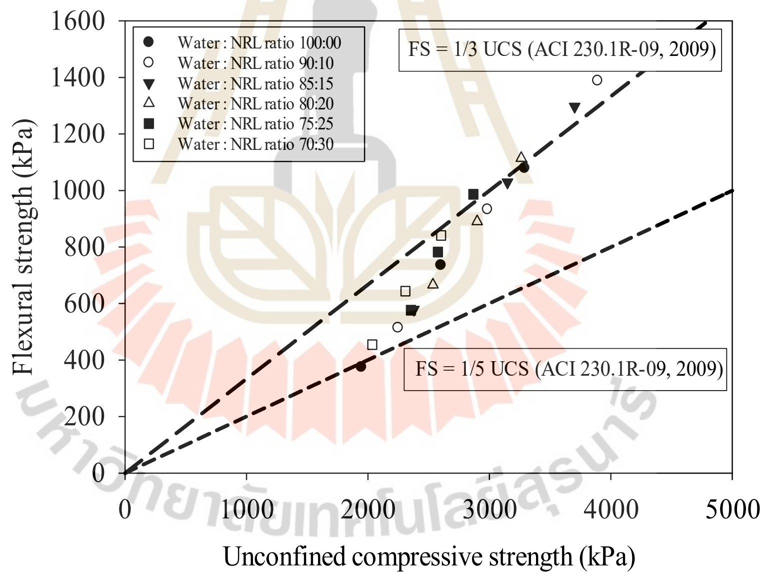

Figure 3.7 Relationship between flexural strength and unconfined compressive strength.

3.5 MICROSTRUCTURAL ANALYSIS

3.5.1 Scanning Electron Microscopic Images

Figure 3.8(a-c) demonstrates the SEM image of cement stabilized samples without NRL after 7 days of curing at 3%, 5%, and 7% cement, repetitively. The cementitious products are observed in pore space. The cementitious products for 3% cement sample are fewer when compared to 5% and 7% cement samples while the highest cementitious products are found at 7% cement. These cementitious products not only fill up the pore space to reduce the void ratio, but also enhance the inter-particle bonding strength, which results in the significant strength development (Horpibulsuk et al. 2010).

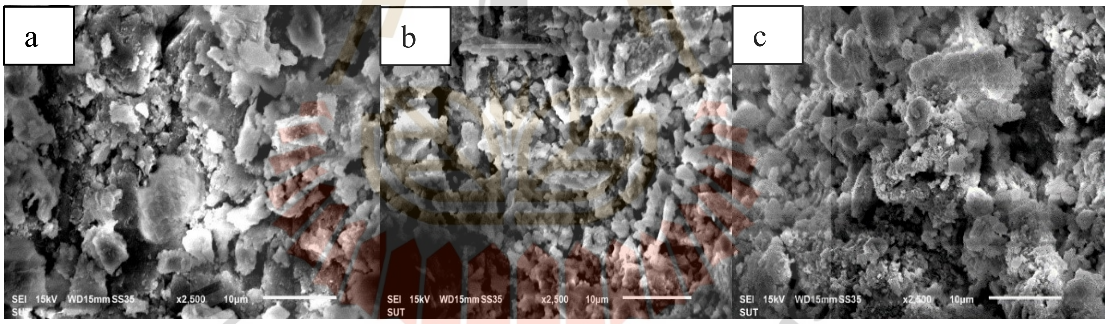

Figure 3.8 SEM images of cement-stabilized soil at (a) 3% cement; (b) 5% cement; and(c) 7% cement.

The SEM images of the cement-NRL stabilized soil samples at optimum NRL replacement ratios and maximum NRL replacement ratio of 30% for 3%, 5%, and 7% cement are presented in **Figures 3.9-3.10**, respectively. **Figure 3.9** shows clearly the coexistence between soil-cement and NRL films for all cement contents. The latex film is infiltrated in pore space and reduces the porosity. The micro-cracks are coated with interconnected films that cover soil particles under cement hydration products. The presence of more latex matrix is found for lower cement content due to higher optimum NRL replacement ratio.

Thicker and more continuous films are detected for 3% cement sample (**Figure 3.9a**). While, the small latex films are plentifully distributed in the pore space for samples with higher cement contents (**Figures 3.9b** and **3.9c**). Only thin and few latex films are appeared within the enormous cement structures and pore space, with very little continuous film network. It is therefore manifested that the samples with lower cement content allow more NRL replacement to complete a strong and dense packing state (highest strength and density).

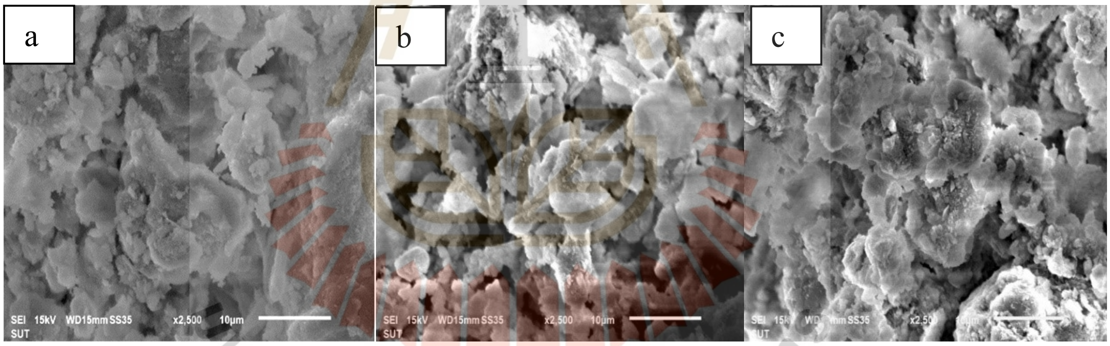

Figure 3.9 SEM images of samples at (a) 3% cement; (b) 5% cement; and (c) 7% cement and at optimum NRL replacement ratios.

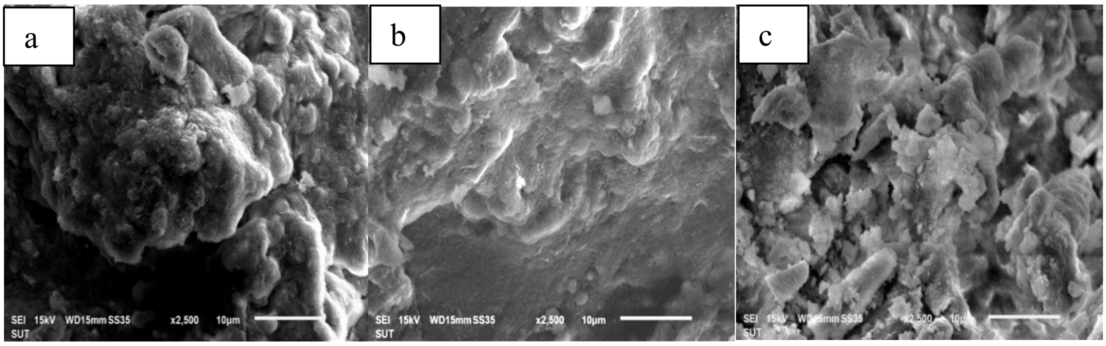

Figure 3.10 SEM images of samples at (a)3%cement;(b)5% cement and (c) 7% cement and at maximum NRL replacement ratios.

At the maximum 30% NRL replacement ratio (**Figure 3.10**), the soil-cement matrix is covered with the excessive NRL film network, which forms a jelly-like surface. This causes the loose soil-cement structure with low density for all cement contents. Moreover, the coating of latex network acts as the barrier-like reaction, which inhibits water absorption of hydration process (Yaowarat et al. 2019). Consequently, the hydration progress is retarded, resulting in the reduction in both UCS and FS.

3.5.2 Energy Dispersive X-ray Spectroscopy (EDS)

The EDS technique by using area mapping analysis at corresponding area in the SEM testing was carried on the 3% cement stabilized samples with and without NRL and the resuts are shown in **Figure 11(a-c)**. This 3% cement samples were chosen because it contained more NRL participation than other samples.

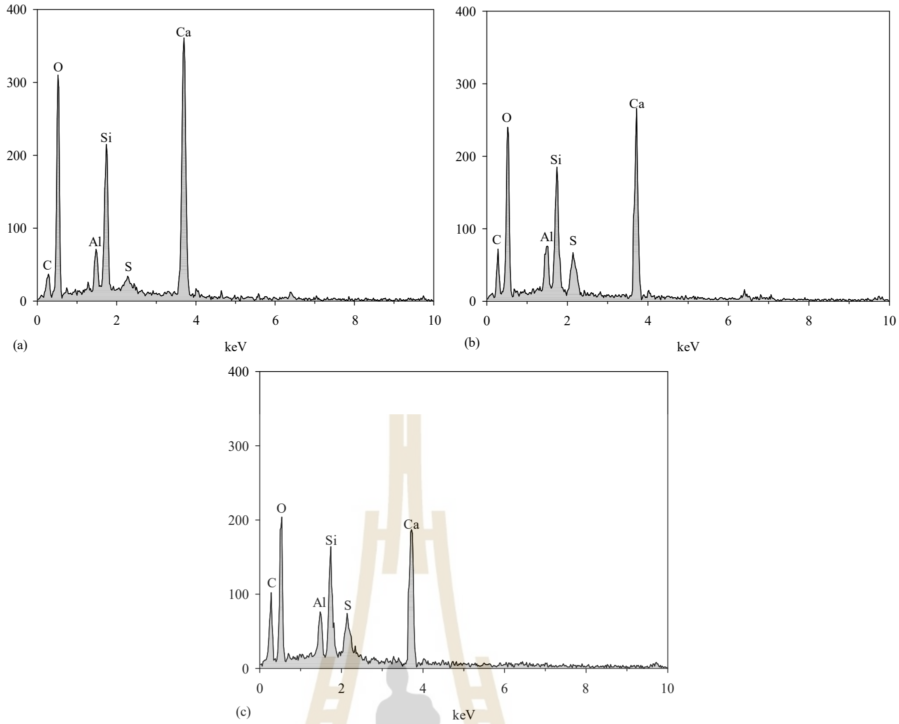

Figure 3.11 EDS result of 3% cement samples for (a) without NRL; (b) optimum NRL; and (c) maximum NRL.

The occurrence of C-S-H for the sample without NRL is detected by the prominent peaks of Ca and Si that are the major elements of hydration products as indicated in **Figure 11a**. Several previous researches work in biological and applied polymer innovation by using the EDS analysis have revealed that the major component of *cis*-1,4-Polyisoprene in solid state of treated and untreated NRL consisted of carbon (C) more than 90% of atoms and other components such as hydrogen (H), zinc (Z_n), silicon (S_i) less than 10% of atoms. (Ho and Khew 1999, Herculano et al. 2011, Rathnayake et al. 2012). Therefore, NRL matrix is generally contained carbon as the major element.

At optimum NRL replacement ratio (**Figure 11b**), the hydration retardation due to the addition of NRL causes the decrease of C-S-H as seen by the lower peaks of Ca and Si elements and the increase of C element from NRL as compared with the 3% cement sample without NRL (**Figure 3.11a**). This implies that although the growth of cementitious products is interrupted, the significant improvements of both compressive and flexural strengths are due to the adhesive bonding strength of latex within soil-cement matrix. The excessive NRL replacement extremely prevents the growth of hydration products (**Figure 11c**). The retardation effect is detected by the appearance of lowest apex of Ca and Si and highest C element compared with the sample without NRL (**Figure 11a**).

From SEM and EDS analysis, the highest compressive and flexural strength is found to be at optimum NRL replacement ratios, which are 20%, 15% and 10% for 3%, 5% and 7% cement contents. The lowest UCS and FS values are observed at the maximum NRL replacement ratio of 30% for 5% and 7% of cement. While the lowest UCS and FS values for 3% cement is found at 0% NRL replacement ratio. For 3% cement, the slight decrease of UCS after optimum NRL is caused by excessive NRL in the solid phase. At low cement content, the hydration slightly affects strength development therefore the NRL replacement plays a significant role on the strength development by enhancing the latex network in the soil-cement matrix. As such, the cement stabilized soil sample at very high 30% NRL replacement ratio still have higher UCS than the sample without NRL. While at high cement content (5% and 7%), the UCS contribution is strongly from the cementation bonding. Though the latex film can enhance the adhesion of the soil-cement matrix, at the same time it retards the cement hydration. Hence, the optimum NRL replacement ratio reduces with increasing the cement content. Consequently, lowest strength is appeared at the maximum of 30% NRL replacement ratio for both of 5% and 7% cement content.

3.6 CONCLUSION

This research studied the influence of natural rubber latex (NRL) on the improvement of mechanical strengths investigation of cement stabilized soil for pavement applications. The microstructural analysis was also carried out on the cement-NRL stabilized soil to examine the influence of NRL. The conclusion can be drawn as follows:

1. The compatibility, compressive strength, and flexural strength of cement stabilized soil could be improved by NRL replacement. The NRL replacement lubricated the soil particles and led to the dense structure after compaction. The cementation and latex film network enhanced the interparticle bonding strength, consequently, both of compressive strength and flexural strength were increased.

2. The highest dry density, compressive strength, and flexural strength for each cement content were observed at the optimum NRL replacement ratio. The optimum NRL replacement ratio is lower for the higher cement content, which are 20%, 15% and 10% for 3%, 5% and 7% cement content, repetitively

3. The mirostrructural analysis confirmed the influence of latex matrix on the mechanical strength improvement. At the optimum NRL replacement ratio, the thick and continuous films of NRL were clearly observed for low cement content of 3%, while the thinner latex films within the soil-cement matrix were detected at higher cement contents of 5% and 7% cement content. This indicates that the samples with lower cement content can absorb more NRL at the densest packing stage.

4. At the optimum NRL replacement ratio, the UCS was improved up to 30%, 21% and 18% for 3%, 5% and 7% cement contents. While, FS was improved up to

78%, 40% and 29% for 3%, 5% and 7% cement contents. The FS to UCS ratios laid between 1/5 and 1/3, which are in agreement with the ACI 203 (2009).

5. The NRL replacement enhances the interparticle cohesion but at the same time it retards the cementation bonding as seen by the EDS analysis result. As such, the mechanical strengths of the cement-NRL stabilized soil decreased when the NRL replacement ratios exceeded the optimum value. The excess latex content took place the soil-cement matrix in the solid phase and caused the loose and weak structures.

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CHAPTER IV

DURABILITY IMPROVEMENT OF CEMENT STABILIZED PAVEMENT BASE USING NATURAL RUBBER LATEX

4.1 Statement of problem

The Southeast Asia region is the biggest natural rubber producer in the world. The production of rubber in this region is more than 50% of the total rubber production worldwide. The top three countries include Thailand, Indonesia, and Vietnam. According to the statistical data in 2019 of the Rubber Authority of Thailand, Thailand had the largest natural rubber export, contributing approximately 38.82% of the world rubber market (Thailand Rubber Authority 2019).

Natural rubber latex (NRL) is a biopolymer from the Hevea brasiliensis tree. The raw state of NRL consists of polymer content (cis-1,4-Polyisoprene) and water. The solid polymer content consists of approximately 94% rubber hydrocarbon and 6% non-rubber substances, such as phospholipids, and protein. The morphology evidence essentially indicates the rubber particles to be spherical in shape and with a random stuffing arrangement.

This particle is typically surrounded by a layer of phospholipids and proteins. The existence of these non-rubber substances causes undesirable attributes, such as premature coagulation. In order to overcome the negative characteristic of NRL, it is usually modified with an additional substance. Ammonia is an additive substance, which balances the charge between proteins and phospholipids, which results in the stability of the latex particles (Nawamawat et al. 2011, Afiq and Azura 2013, Norhanifah et al. 2015, Ho and Khew 1999, Herculano et al. 2011, Rathnayake et al. 2012, Sakdapipanich 2007).

However, ammonia evaporates easily when it reacts with cement, resulting in instantaneous coagulation of latex (Nagaraj et al. 1988). Consequently, for cement and concrete applications, the sodium dodecyl sulfate (SDS) is suggested as a surfactant. This additive has the potential to eliminate the bonding of non-rubber compounds. The NRL residual products after the treatment thereafter becomes a water and water-soluble component. Subsequently, the SDS replaces the non-rubber layers and covers the latex particles to prevent coagulation (Vo and Plank 2018).

The application of NRL in civil engineering works has been reported by previous researchers. NRL has the potential to improve the viscosity and elastic recovery of the asphalt binders (Wen et al. 2017). Moreover, NRL in the cement matrix can enhance compressive and tensile strengths because it can form latex films within a concrete matrix, which serves as a nano-reinforcement material. As such, it can improve the strain capacity before failure, resulting in ductile behavior (Sukmak et al. 2020). However, excess NRL retards the hydration in cement and concrete due to the excessive latex film (Nagaraj et al. 1988, Muhammad et al. 2011, Muhammad et al. 2012, Muhammad and Ismail 2012, Vo and Plank 2018).

In addition to the usage of NRL in buildings, NRL can be applied in road construction. Roads are the major transportation infrastructure in Asian countries, including Thailand. The Thailand Office of Transport and Traffic Policy and Planning (2018) reported that the growth rate of Thailand's transportation network was more than 50% per annum.

Cement stabilized soil as pavement base and sub-base materials has been extensively applied in various countries to solve the shortage of high-quality materials (Horpibulsuk et al. 2006, Zhang and Tao 2008). The utilization of cement considerably improves the physical and mechanical strength properties of pavement structures (base and subbase) and also the resistance to deformation, permeability, and durability of the pavement structure. The stabilization mechanism of cement stabilized soil is related to the hydration system, in that the cementation products gradually developed in the voids among aggregates and bond the soil particles together (Zhao et al. 2016, Horpibulsuk et al. 2006, Khoury and Brooks 2010, Rosenbalm and Zapata 2017, Sobhan and Das 2007).

Nevertheless, the cement stabilized soil, especially with high fine contents, exhibits brittle behavior and extremely low flexibility, which causes macro and micro cracks when subjected to static and repeated loads (Jamsawang et al. 2015). Recently, Buritatum et al. (2020) reported that NRL as an additive could improve the compressive and flexural strengths of cement stabilized pavement base material. Besides the mechanical strength, cement stabilized soils in tropical countries are subject to cracking problems and premature pavement distress, due to the cyclic wet and dry seasons (Chen et al. 2011).

The durability against wetting and drying cycles are a long-term performance criterion of the pavement structure to assess the stability under number of exposures to natural disaster. Southeast Asian nations, including Thailand, usually suffers a variation of extreme climate, especially drought and flooding phenomena. These calamities could be considered as a serious effect on the service life of the pavement structure. In order to investigate the effect of weathering change on the damage of pavement materials, the durability against wetting-drying (w-d) cycles in accordance with ASTM D559 is commonly adopted.

The swelling and shrinkage upon w-d cycles accelerate the premature failure of the stabilized pavement base/subbase materials. In the drying process, the extremely decreased water content causes the suction force development until the surface tensile stress overcomes the cohesion strength of the materials, causing the crack formation. The crack formation continuously generates with the further change of moisture content until the external surface fractures exist due to irrecoverable deformation, which causes a reduction in the stability of materials. Therefore, the evaluation of service life of stabilized material via durability against w-d cycles test is significant (Biswal et al. 2019, Solanki and Zaman 2014, Yazdandoust and Yasrobi 2010, Khoury and Zaman 2002, Consoli et al. 2018, Beriha et al. 2018, Hoy et al. 2017, Suddeepong et al. 2018).

In order to improve the serviceability and durability of pavement structures, the combined usage of both cement and polymer is an effective solution. The cement gel formation can improve particle bonding while the polymer film formation enhances the elastic properties and reduces the degree of swelling and shrinkage. As such, volumetric stability to prevent weight and strength loss is effectively improved with the polymer matrix (Chittoori et al. 2018, Yazdandoust and Yasrobi 2010, Starcher et al. 2016).

To the best of the authors' knowledge, there has been no research undertaken to date on the usage of NRL in pavement geotechnics to improve the durability of cement stabilized pavement base/subbase, which is the focus of this research. The effect of influence factors including types of soil, type of NRL, NRL replacement ratio and cement content on the cyclic w-d compressive strength and weight loss was examined in this research study. Based on the critical analysis of the experimental results, the strength predictive equation at various w-d cycles was proposed, using the initial unconfined compressive strength without w-d cycle (UCS_0) as the prime factor. Moreover, the carbon footprint of cement-NRL stabilized soil and cement stabilized soil at the same UCS_0 was evaluated. The outcome of this research will result in the promotion of NRL utilization as a sustainable additive in cement stabilized pavement base/subbase courses in Thailand and other Southeast Asia countries.

4.2 Materials

4.2.1 Soil Sample

Lateritic soil is a common pavement material in the tropical region, especially in Southeast Asia. In this research, two different lateritic soils (Soil A and Soil B) were used. Soil A and Soil B were excavated from a borrow pit in Nakhon Ratchasima and Saraburi provinces, Thailand, respectively. Grain size distribution curves of both soils were illustrated in **Figure 1**. According to the Unified Soil Classification System, Soil A was classified as GP-GC while Soil B was as the GC. Soil A had less plasticity index than Soil B. Basic and engineering properties of both soils are summarized in **Table 1**.

According to the standard of Department of Highways, Thailand (DH-S201/2544, DH-S205/2532), both studied soils did not meet the minimum requirements for base and subbase materials due to high plasticity index and low CBR. However, the properties of both materials meet the criteria for cement stabilized base according to the DH-S204/2532 standard.

4.2.2 Cement

Ordinary Portland cement (Type I), which is commonly used in stabilization of pavement materials worldwide, was selected to stabilize Soil A and Soil B. The 7-day and 28-day compressive strengths were measured to be 27.4 MPa and 32.6 MPa, respectively. The compositions of cement are illustrated in **Table 4.2**

Table 4.1 Basic and Engineering Properties of Studied Soils

Sample Properties	Soil sample A (GP-GC)	Soil sample B (GC)	Standard for base materials DH-S201/2544	Standard for sub-base materials DH-S205/2532	Standard for stabilization of base materials DH-S204/2532
	Values				
Largest particle size	25.4	37.5	≤ 50	≤ 50	≤ 50
(mm)	34	42	≤ 40	≤ 60	≤ 60
Los Angeles abrasion	21	28	≤ 25	≤ 35	≤ 40
(%)			≤ 6	≤ 11	
Liquid limit LL (%)					
Plastic limit PL (%)	8	13			-
Plasticity index PI (%)	14	15	≤ 6	≤ 11	≤ 15
Specific Gravity (G_s)	2.78	2.71	-	-	-
Maximum dry density (kN/m^3)	20.87	19.86	-	-	-
Optimum water content (%)	8.07	9.24	-	-	-
California bearing ratio (%)	18.16	13.01	≥ 80	≥ 25	-

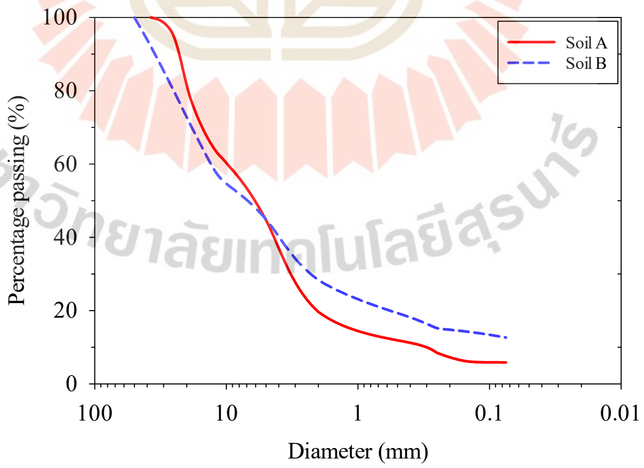

Figure 4.1 Particle size distributions of studied soils.

Table 4.2 Chemical Compositions of Cement.

Composition	Value (%)
Silicon dioxide (SiO_2)	20.7
Sulphur oxide (SO_2)	4.8
Ferric oxide (Fe_2O_3)	3.1
Aluminium oxide (Al_2O_3)	4.7
Calcium oxide (CaO)	65.3
Magnesium oxide (MgO)	2.8
Loss on ignition (LOI)	0.9

4.2.3 Natural Rubber Latex (NRL)

In order to investigate the role of dry rubber content (DRC) in total unit volume, the three types of NRL with different DRC from 30% to 40% by total weight of NRL were used. The studied NRLs included Type 1 (DRC = 30%), Type 2 (DRC = 35%) and Type 3 (DRC = 40%). All NRLs were treated with deproteinization agents (Norhanifah et al. 2015), which are sodium dodecyl sulphate (SDS), zinc 2-mercaptobenzothiazole (ZMBT), zinc oxide, calcium carbonate, and sulphur substance to improve workability and remove undesired characteristics of NRL such as the premature coagulation with cement reaction (Nagaraj et al. 1988). Since NRL is in the liquid form, the NRL content was determined in term of the replacement ratio by a total liquid content, which is convenient for field works.

4.3 Experimental procedures

4.3.1 Preparation and testing condition

The 28-day unconfined compressive strength (UCS) requirement for cement stabilized sandy and gravel soils is recommended to be between 2.76 and 6.89 MPa (ACI 230, 2009; Little and Nair, 2009). Therefore, the cement content (C) of 3%, 5%, and 7% were selected for this study, which results in the UCS values being in this range. Both soil samples were sieved to remove the aggregates which were coarser than 19 mm, by the wet method. Portland cement was then mixed with the air-dried soil samples and compacted under the modified Proctor test in accordance with ASTM D1557 to determine maximum dry density (MDD) and optimum water content (OWC). According to the DH-S204/2532 standard, the cement stabilized base materials are required to compact under modified Proctor energy. The soil-cement mixture was next mixed with liquid (water and NRL) to reach OWC at various NRL replacement ratios of 10%, 15%, 20%, 25% and 30% by weight of water. Since all studied NRLs were used to replace water at the same replacement ratio, the initial DRC is the suitable parameter for investigating the effect of DRC on the UCS development in cement-NRL cement stabilized soils. The samples were statically compacted in a metallic mold with dimensions of 101.60 mm diameter and 116.8 mm height under modified Proctor energy at optimum liquid content to reach MDD. Subsequently, the compacted samples were demolded after 24 hours and wrapped by plastic sheets. These samples were kept in a 95% relative humidity room at 25 °C until UCS tests at 28 days of curing and at various w-d cycles.

4.3.3 Unconfined compressive strength

According to ASTM D1633 standard, at least 3 samples were conducted to ensure the reliability of the test result. The UCS tests on 28 days cured samples were conducted at a deformation rate of 1 mm/min, using a universal testing machine with an automatic data recorder.

4.3.4 Wetting and drying durability

The durability tests against w-d cycles on cement stabilized soil samples were performed in accordance with the ASTM D559 standard. In this study, the samples were subjected to a maximum of 12 wetting-drying (w-d) cycles. Each cycle consists of 5 hours of deionized water submersion at room temperature followed by the drying process at a temperature of 70oC in an oven for 42 hours. The weight loss of samples at each cycle was also recorded. At a target w-d cycle, the samples were immersed in deionized water for 2 hours and air-dried for at least 1 hour prior to the UCS test. The UCS was measured at 1, 3, 6, 9, and 12 w-d cycles.

4.4 RESULTS AND DISCUSSION

Figures 4.2 and **4.3** illustrate the influence of NRL replacement ratio on UCS of the cement stabilized Soil A and B for the various types of NRL. It is evident that the cement-NRL stabilized samples have higher UCS values than the cement stabilized samples, for all cement contents and NRL replacement ratios tested. The strength development is due to the composite between cement hydration and the latex film formation. Muhammad et al. (2012) reported that the cohesive strength of NRL modified concrete was enhanced with interconnected NRL within micro-pores, which served to be the reinforcement. The NRL films enhance the cohesion of soil particles but meanwhile, they retard the hydration (Vo and Plank 2018, Nagaraj et al. 1988, Buritatun et al. 2020). The Scanning Electron Microscopic (SEM) and Energy Dispersive X-Ray Spectroscopy (EDS) results (Buritatun et al. 2020) indicated that the cement-NRL stabilized soil exhibited dense structures. The NRL films coat micro-crack and fill the void space, resulting in the cohesive strength gain. However, the C-S-H of cement-NRL stabilized soil decreased as the increased NRL. This is evident by the lower peaks observed of Ca and Si elements and higher peaks observed for the C element (a major element of NRL).

The excess NRL content causes the coagulation effect between cementitious products and NRL film (Nagaraj et al. 1988). The incompatibility of the coagulated particles causes a negative effect on bonding strength development. For a given cement content, the highest UCS value is achieved at an optimum NRL replacement ratio. The highest UCS results from the best combination of cementation bond strength from hydration products and soil-particles cohesion from NRL films. At low cement content, the hydration slightly affects the strength development, whereby the NRL participation from higher NRL replacement ratio is dominant. Whereas at high cement contents however, the retardant effect from NRL replacement is dominant and the reduction in cementation bond strength cannot be compensated by the increased soil-particles cohesion. As such, the optimum NRL replacement ratio reduces with the increased cement content, which is 20%, 15%, and 10% for 3%, 5%, and 7% cement, respectively.

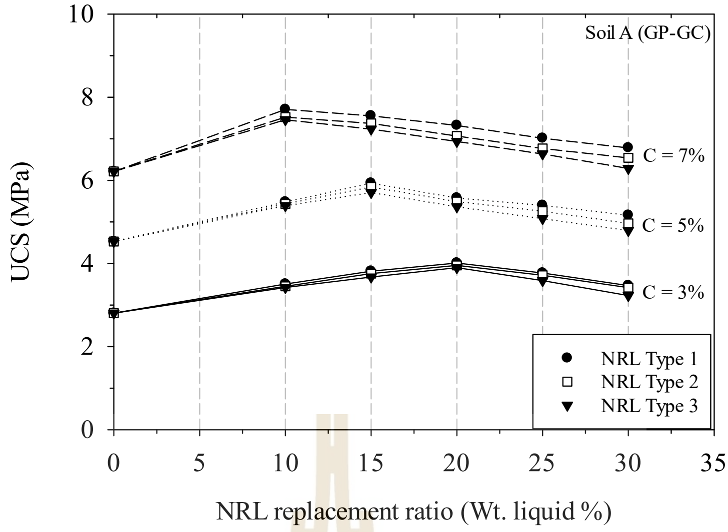

Figure 4.2 Unconfined compressive strength for different cement contents and NRL replacement ratios of NRL type 1, NRL type 2, and NRL Type 3 of Soil A.

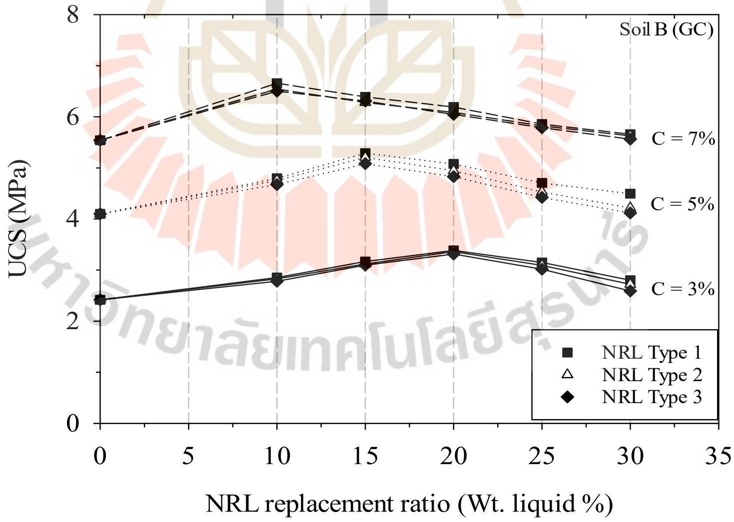

Figure 4.3 Unconfined compressive strength for different cement contents and NRL replacement ratios of NRL type 1, NRL type 2, and NRL Type 3 of Soil B.

The influence of DRC on the UCS development for cement stabilized soil can also be observed in **Figures 4.2** and 4.3. For both soils, the UCS values are lower for the higher DRC at the same cement contents and NRL replacement ratios. The highest UCS is found for NRL Type 1 (lowest DRC) and followed by NRL Type 2 and NRL Type 3. The higher DRC is accompanied by the higher non-rubber substance, causing more premature coagulation and cement retardation (Muhammad et al. 2012). However, DRC has an insignificant effect on the optimum NRL replacement ratio.

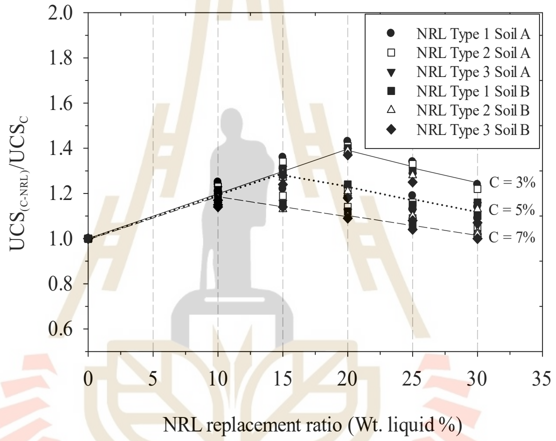

Figure 4.4 Relationship between $UCS_{(C\text{-}NRL)}/UCS_{(C)}$ and NRL replacement ratios for Soil A and Soil B at 3% cement content, 5% cement content, and 7% cement content.

The soil type affects the UCS development, as it is evident that Soil A has higher UCS values than Soil B for the same cement contents and NRL replacement ratios. As LL controls the OWC of compacted soils (Horpibulsuk et al. 2008 and 2009), Soil A has lower OWC than Soil B and hence higher UCS at the same C due to the lower water to cement ratio (Horpibulsuk et al. 2005)

To investigate the role of the soil type, NRL type, cement content and NRL replacement ratio on the UCS development, the normalized $UCS_{(C\text{-}NRL)}/UCS_{(C)}$ (ratio of UCS values of cement-NRL stabilized soils to UCS values of cement stabilized soils) against NRL replacement ratio was plotted and is shown in **Figure 4.4** for the 3 NRL types and for Soil A and Soil B at C = 3%, 5% and 7%. It is evident that NRL and soil types insignificantly affect the normalized $UCS_{(C\text{-}NRL)}/UCS_{(C)}$ at the same cement content and NRL replacement ratio. The maximum normalized $UCS_{(C\text{-}NRL)}/UCS_{(C)}$ is found at NRL = 10%, 15% and 20% for C = 7%, 5% and 3%, respectively, which is approximately 1.43, 1.31 and 1.24 for 3%, 5% and 7%, respectively. With the similar slope of the plot at pre-peak, it is implied that the NRL replacement is akin to an addition of cement and the rate of strength improvement over NRL replacement ratio is the same for both soils and the three NRL types.

Figures 4.5 and **4.6** present the weight loss referenced to the initial weight of the sample, at various w-d cycles. The cement stabilized Soil A and Soil B even without NRL can remain stable until the end of 12 w-d cycles with the weight loss being within the acceptable range (not excess 14%) according to the ACI recommendation for cement stabilized granular materials (ACI 230, 2009). For all cement contents tested, the weight loss for both Soil A and Soil B, rapidly increases with w-d cycles. However, after the 6^{th} w-d cycle, the weight loss gradually increases with w-d cycles. Throughout the cyclic w-d test, both macro- and micro-cracks were developed (Neramitkornburi et al. 2015, Suddeepong et al. 2018) due to the shrinkage and swelling caused by the loss and the absorption of moisture, respectively. The higher cement content strengthens interparticle contacts against the shrinkage and swelling at lower void space (Biswal et al. 2019), resulting in the smaller weight loss.

The maximum weight loss is found at C = 3% and it is 10.75% and 13.30% for Soil A and Soil B at 12^{nd} w-d cycle. Hoy et al. (2017) reported that the early w-d cycles caused mainly micro-cracks in the stabilized material and weakened the inter-particle bonds. Consequently, the loss of small particles happens significantly, which results in the significant weight loss when the w-d cycles < 6. On the other hand, the micro-cracks are almost fully developed when the w-d cycles > 6, resulting in the smaller rate of weight loss over w-d cycles.

Due to the higher fines content and larger optimum liquid content, the cement stabilized Soil B is more sensitive to moisture changes during the w-d cycles. As such, the weight loss in cement stabilized Soil B is larger than that in cement stabilized Soil A at the same w-d cycles (compared **Figures 4.5a** and **4.6a**). For example, at 12^{th} w-d cycle, the weight loss of cement stabilized Soil A is 10.75%, 9.09% and 7.21% at C = 3%, 5% and 7%, respectively while the weight loss of cement stabilized Soil B is 13.30%, 11.22% and 9.01% at C = 3%, 5% and 7%, respectively.

At the same cement content, the weight loss of cement-NRL stabilized soil is evidently smaller than that of cement stabilized soil for both Soil A and Soil B. Similar to the UCS result, the lowest weight loss is found at the optimum NRL replacement ratios for all 3 types of NRL and both Soil A and Soil B, which are 20%, 15%, and 10% for C = 3%, 5%, and 7%, respectively.

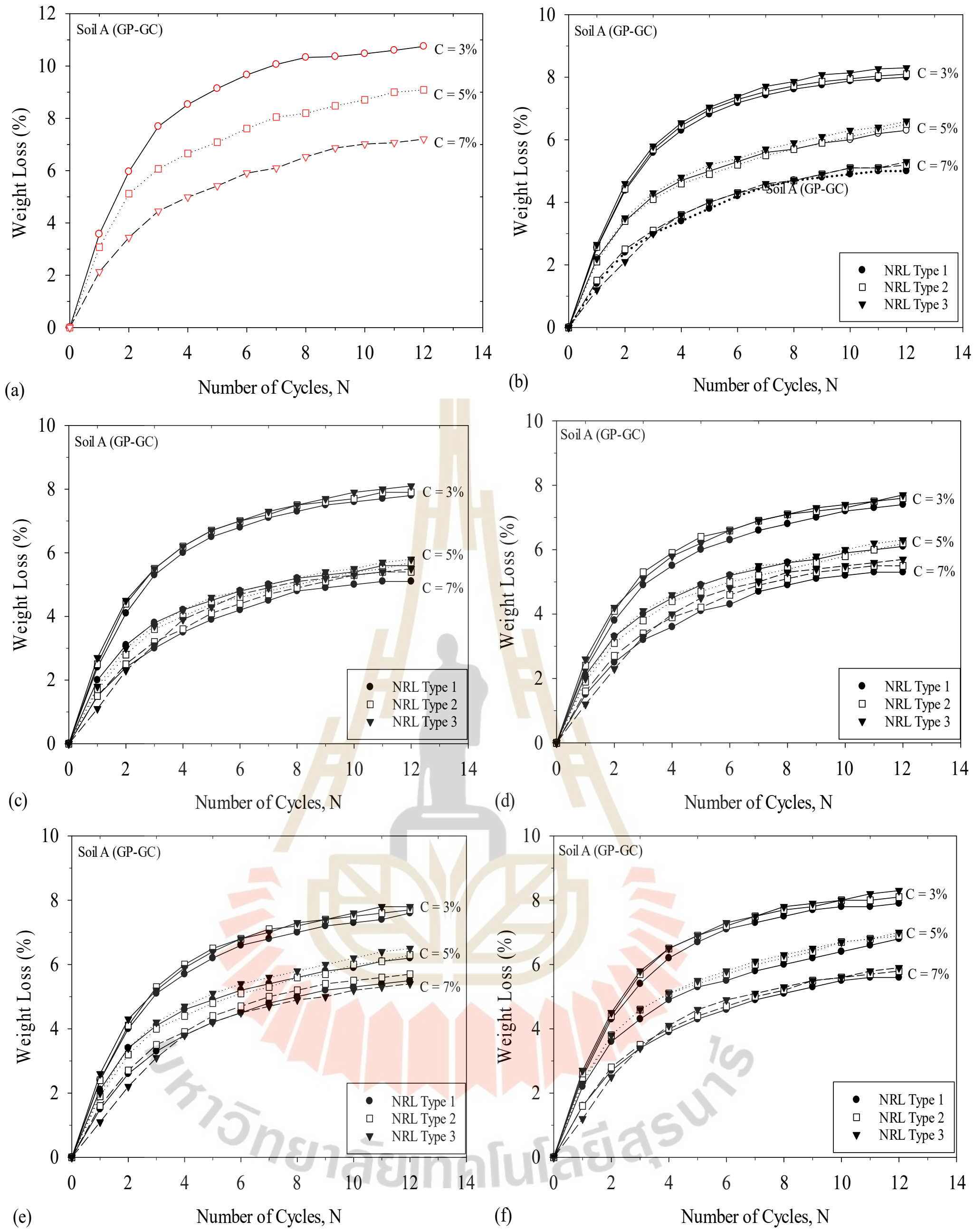

Figure 4.5 Relationship between weight loss and number of w-d cycles at various cement contents and NRL types for (a) 0% NRL, (b) 10% NRL, (c) 15% NRL, (d) 20% NRL, (e) 25% NRL, and (f) 30% NRL of soil A.

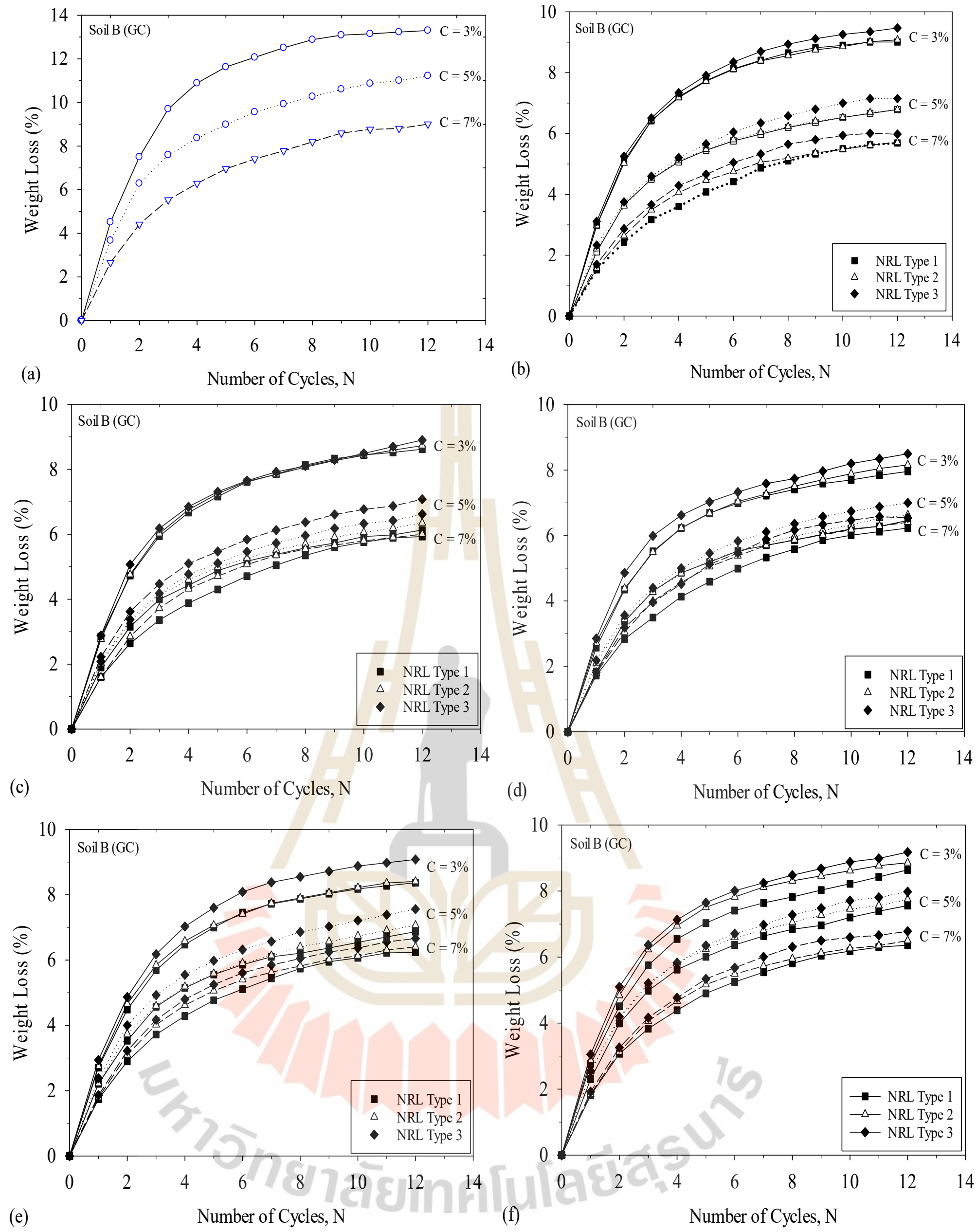

Figure 4.6 Relationship between weight loss and number of w-d cycles at various cement contents and NRL types for (a) 0% NRL, (b) 10% NRL, (c) 15% NRL, (d) 20% NRL, (e) 25% NRL, and (f) 30% NRL of soil B.

For example, at C = 3% and for NRL Type 1, the weight loss of cement-NRL stabilized Soil A at 12^{th} w-d cycles is 8.01%, 7.75%, 7.40%, 7.64% and 7.95%, for NRL replacement ratio = 0%, 10%, 15%, 20%, 25% and 30%, respectively. Although the values of weight loss of the cement-NRL stabilized Soil A and Soil B are the highest at NRL replacement = 30%, the values are still lower than those of the cement stabilized Soil A and Soil B.

The effect of DRC and soil type on the weight loss of the cement-NRL stabilized soil is noticed. The weight loss of stabilized Soil B is higher than that of stabilized Soil A and the lowest weight loss is found at NRL Type 1 (the lowest DRC), followed by NRL Type 2 and NRL Type 3. For example, at optimum NRL replacement ratio and at C = 3%, the weight loss at 12^{th} w-d cycle of cement-NRL stabilized Soil A is 7.40%, 7.57%, and 7.65% for NRL Type 1, Type 2, and Type 3, respectively and the weight loss at 12^{th} w-d cycle of cement-NRL stabilized Soil B is 7.96%, 8.27%, and 8.65% for NRL Type 1, Type 2, and Type 3, respectively.

Figures 4.7 and **4.8** present the relationship between the w-d cycled strength ($UCS_{(w-d)}$) versus the number of cycles of the cement-NRL stabilized Soil A and Soil B, respectively for 3 types of NRL at different NRL replacement ratios. The reduction in UCS for cement stabilized Soil A and Soil B without NRL is clearly noted with the increased number of w-d cycles, N (*see* **Figures 4.7a** and **4.8a**). Associated with the large weight loss at w-d cycles < 6, the remarkable UCS reduction with increasing N is clearly noted due to the loss in inter-particle bonds caused by the micro-cracks.

Even with small weight loss over w-d cycles when *N*> 6 (**Figures 4.4** and 4.**5**), the reduction in UCS still exists. At this stage, the growth of the micro-crack formation generated the macro-cracks, which intensify with the increased *N* (Suddeepong et al. 2018). The cement stabilized Soil B with a higher weight loss has lower UCS than the cement stabilized Soil A at the same *N* values. For a particular soil, the samples with higher cement content shows higher $UCS_{(w\text{-}d)}$ than the samples with lower cement content at the same w-d cycles.

For example, the $UCS_{(w\text{-}d)}$ at 12^{th} w-d cycle is 0.35 MPa, 0.73 MPa, and 1.21 MPa for Soil A at C = 3%, 5%, and 7%, respectively. The more cementitious products create stronger matrix with high inter-particle forces and small pores, which can prevent the degradation of samples from the attack of w-d cycles (Ahmed and Ugai, 2011).

It is evident from **Figures 4.7** and **4.8** that cement-NRL stabilized soil evidently presented a higher $UCS_{(w\text{-}d)}$ than the cement stabilized soil (without NRL). As expected, a highest potential of NRL replacement on the improved $UCS_{(w\text{-}d)}$ is found at the optimum NRL replacement ratio: 20%, 15% and 10% for 3%, 5%, and 7% cement, respectively, for both Soil A and B with all types of NRL. For example, at C = 3% and NRL Type 1, the $UCS_{(w\text{-}d)}$ at 12^{th} cycle is 0.92 MPa, 1.10 MPa, 1.37 MPa, 1.19 MPa, and 1.05 MPa for Soil A, meanwhile the $UCS_{(w\text{-}d)}$ for Soil B is 0.70 MPa, 0.88 MPa, 1.07 MPa, 0.78 MPa, and 0.69 MPa for Soil B at 10%, 15%, 20%, 25%, and 30% NRL replacement ratios, respectively.

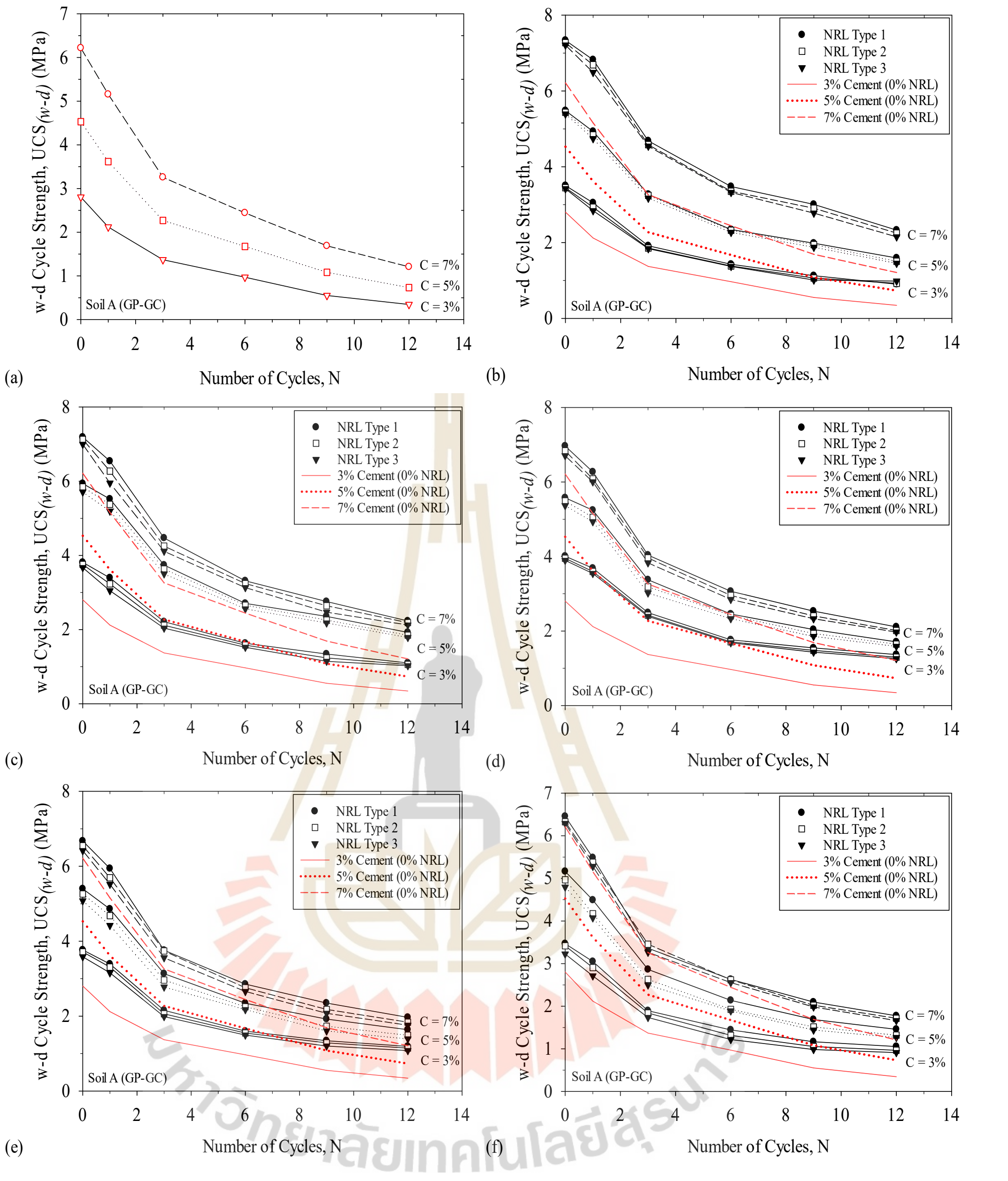

Figure 4.7 Relationship between w-d cycle strength and number of w-d cycles at various cement content and NRL types for (a) 0% NRL, (b) 10% NRL, (c) 15% NRL, (d) 20% NRL, (e) 25% NRL, and (f) 30% NRL of soil A.

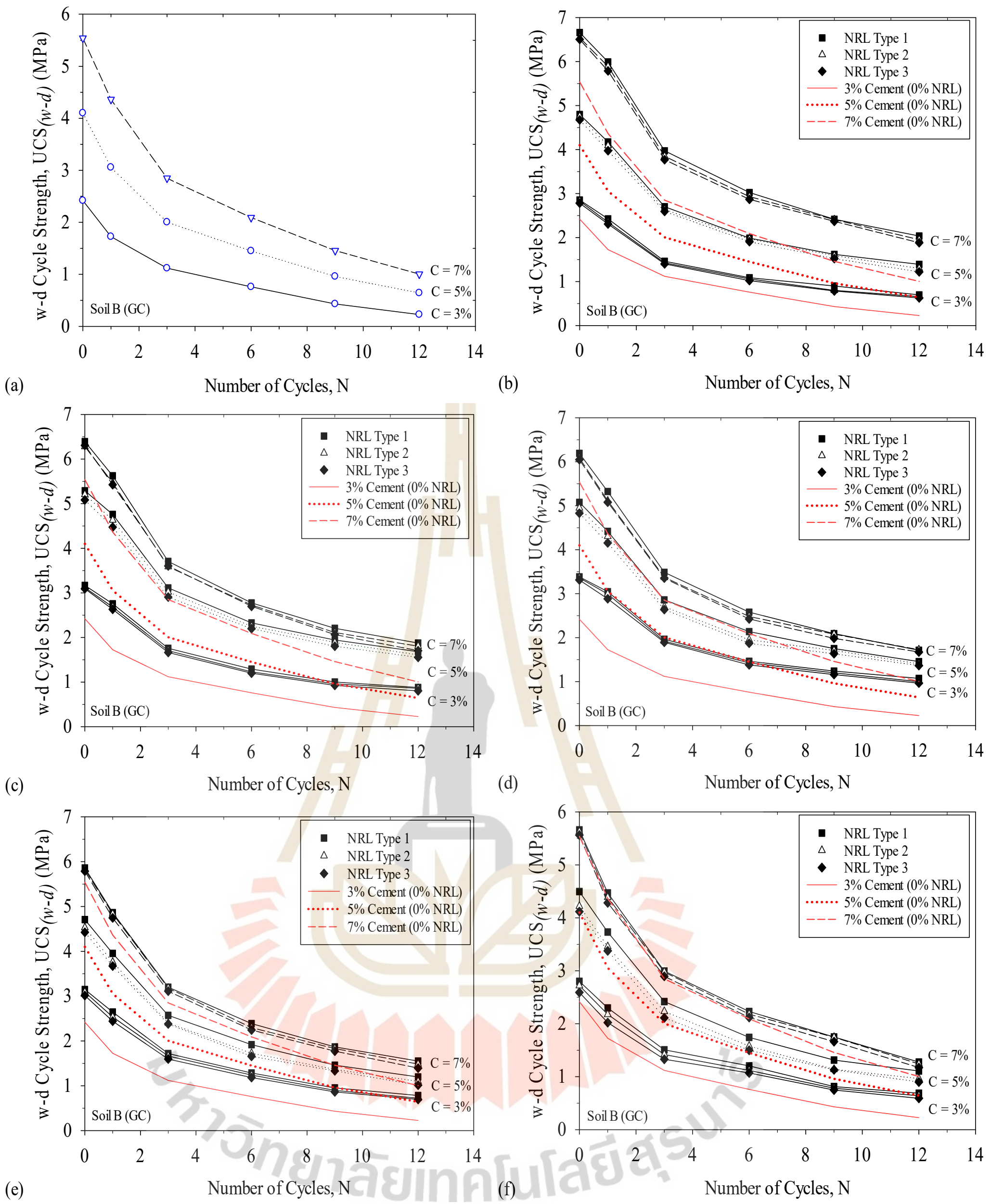

Figure 4.8 Relationship between w-d cycled strength and number of w-d cycles at various cement contents and NRL types for (a) 0% NRL, (b) 10% NRL, (c) 15% NRL, (d) 20% NRL, (e) 25% NRL, and (f) 30% NRL of soil B.

NRL Type 1 shows a slightly higher potential in providing higher $UCS_{(w-d)}$, followed by type 2 and type 3 for both Soil A and Soil B (**Figures 4.7** and **4.8)**. For instance, the $UCS_{(w-d)}$ values at 12^{th} cycle of Soil A at optimum NRL replacement ratio and 7% cement are 2.33 MPa, 2.24 MPa, and 2.15 MPa and those of Soil B are 2.04 MPa, 1.95 MPa, and 1.88 MPa for NRL Type 1, Type 2, and Type 3, respectively. In addition, the effect of different soil properties between Soil A and Soil B on $UCS_{(w-d)}$ can be observed. Due to the higher fines content, the cement-NRL stabilized Soil B exhibited a lower $UCS_{(w-d)}$ than the cement-NRL stabilized Soil A.

The previous research revealed that the $UCS_{(w-d)}$ at the different N is related to the initial UCS prior to w-d tests (UCS_0) (Neramitkornburi et al. 2015, Suddeepong et al. 2018). Therefore, UCS_0 is considered as a major variable in the analysis of the correlation between the reduction in $UCS_{(w-d)}$ with the increased N. The parameter normalized $UCS_{(w-d)}/UCS_0$ is thus employed to investigate the role of NRL on the resistance to w-d degradation of cement-NRL stabilized soil.

Even though the soil type, NRL type and cement content affect the UCS_0 and $UCS_{(w-d)}$ of cement-NRL stabilized soil, the normalized $UCS_{(w-d)}/UCS_0$ at N is found to be essentially the same. In other words, the normalized $UCS_{(w-d)}/UCS_0$ is primary dependent upon N and irrespective of soil type, NRL type and cement content into account.

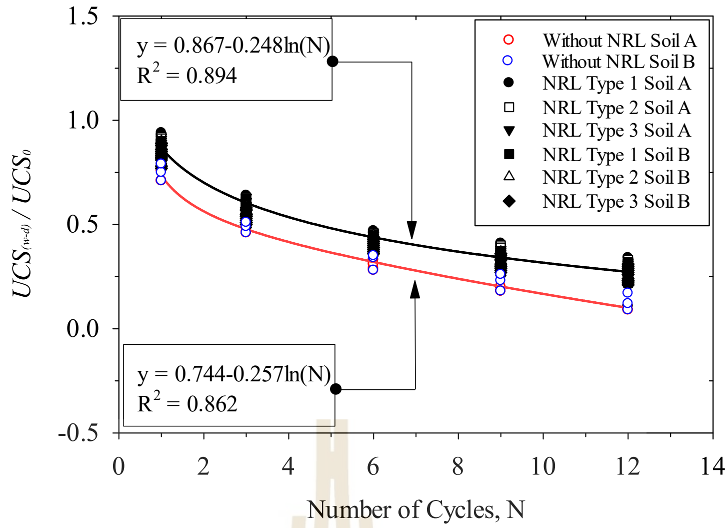

Figure 4.9 Relationship between $UCS_{(w-d)}/UCS_0$ and number of w-d cycles at different cement contents and types of NRL for 0% NRL, 10% NRL, 15% NRL, 20% NRL, 25% NRL, and 30% NRL of Soil A and Soil B.

Figures 4.9 presents the relationship between $UCS_{(w-d)}/UCS_0$ versus N in a logarithm function on the linear scale. The normalized relationship exhibits a unique function for all cement contents, soil types, NRL types, and NRL replacement ratios as follows:

$$UCS_{(w-d)}/UCS_0 = a - b\ln(N) \quad 1 < N < 12 \quad (1)$$

where a and b are constant. From **Figure 4.9**, it is noted that a and b for the cement-NRL stabilized soil are different from those of the cement stabilized soil. The NRL film improves the tensile strength of cement stabilized soil and therefore enhances the UCS_0 and the resistance to strength reduction over w-d cycles. Consequently, the normalized $UCS_{(w-d)}/UCS_0$ versus N relationship of the cement-NRL stabilized soil is above that of the cement stabilized soil, indicating the higher durability against w-d cycles of cement-NRL stabilized soil at the same UCS_0. The a

and *b* values are respectively found to be 0.744 and 0.257 with coefficient of determination R^2 = 0.862 for cement stabilized soil and are 0.867 and 0.248 with R^2 = 0.894 for cement-NRL stabilized soil.

The proposed relationship is very useful to predict the $UCS_{(w\text{-}d)}$ at various *N* for both cement stabilized soil and cement-NRL stabilized soil since the durability test is time-consuming. With this relationship, the $UCS_{(w\text{-}d)}$ can be approximated using UCS_0, which is simply obtained from the conventional strength test. The development of this relationship is on sound principles and can be used to develop strength prediction of other soil types and NRL types.

With a very high R^2 value of 0.894, it can be confirmed that Equation (1) with a = 0.867 and b = 0.248 is valid and within an acceptable engineering acceptance for cement-NRL stabilized soils with NRL replacement ratios between 10% and 30%, DRC between 30% to 40%, cement contents between 3% and 7%, LL < 40% and PI < 15%. More tests on various cement-NRL stabilized soils with cement contents and DRC values are recommended for further research to refine the suitable *a* and *b* values.

4.5 ENVIRONMENTAL ASSESSMENT

Currently, greenhouse gas pollution is intensifying to climate change and global warming. The greenhouse gas emission and environmental impacts from the process regarding product manufacture, including product distribution, usage throughout a product's life, have been assessed through the life cycle assessment. In order to analyze the life cycle assessment, the carbon footprint has been considered as the crucial factor regarding the impacts on the environment, which is a very serious effect compared to the other effect. Consequently, the carbon footprint assessment therefore can be used to evaluate environmental impacts (Lazarevic and Martin, 2016 and McLellan et al. 2011). According to Jawjit et al. (2010), Thailand's greenhouse gas emission from agriculture, industrial, transportation sectors was 286 Tg carbon dioxide equivalent (CO_2-e). Hence, Thailand's government and worldwide have placed stringent measures to reduce greenhouse gas emissions in order to mitigate global warming.

In fact, cement stabilization is a widely used means to strengthen pavement base and subbase. However, the production of cement has emitted pollution with high embodied energy. The carbon dioxide equivalent (CO_2-e) of cement production is equal to 0.86 kg CO_2-e /kg (Turner and Collins 2013 and McLellan et al. 2011). The high cement content utilization is therefore considered to be the risk factor of greenhouse pollution.

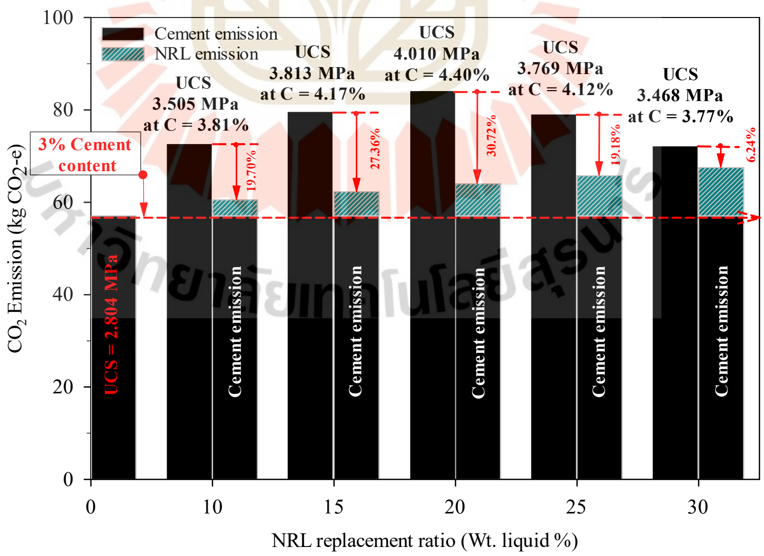

Figure 4.10 Relationship between CO_2-e Emission for cement stabilized Soil A and Soil B with and without NRL.

It is evident from the experimental results that the NRL can reduce the input cement while improve the UCS_0; therefore, the lower carbon footprints emission. The emission factors for the studied materials of cement stabilized soil with and without NRL are summarized in **Table 4.3**. According to Jawjit et al. (2010), the emission factor of concentrated latex of natural rubber, starting from the cultivation and harvest, to the portage, is 0.143 kg CO_2-e /kg. Since the amount of additional substance in NRL is little, the emission factor of NRL is assumed to be 0.143 kg CO_2-e /kg. In the comparison, the carbon footprints due to the transportation of both NRL and cement are not considered as they are essentially the same; both cement and NRL are simply obtained in Thailand's market. In addition, the stabilization process for both cement and cement+NRL is similar; only the NRL is used to replace water for cement+NRL. Therefore, the carbon footprint due to the stabilization process is not considered.

Table 4.3 Emission factors of the studied materials

Material	**Emission factor** (kg CO_2-e/kg)	**References**
Cement	0.86	McLellan et al. (2011)
NRL	0.143	Jawjit et al. (2010)

Turner and Collins (2013) revealed that the emission factor for coarse-grained aggregate has been estimated to be 0.0408 CO_2-e/kg. This value includes quarrying and crushing, and the transportation process. However, it is very low values when compared with the carbon footprint of cement and NRL. Hence, it is ignored from the calculation of carbon footprint.

Figure 4.10 illustrates the carbon footprint emission of the cement-NRL stabilized Soil A at various NRL replacement ratios compared to the cement stabilized Soil A at the same target UCS values. The studied C was 3% and the studied NRL was NRL Type 1 at replacement ratios of 10% to 30%. The cement content of cement stabilized soil to attain the same UCS as cement-NRL stabilized soil was approximated from the experimental results demonstrated in **Figure 4.2**.

According to the analyzed results in **Figure 4.10**, the CO_2-e emission values of cement-NRL stabilized Soil A is lower than that of cement stabilized Soil A for the same target UCS value. At the UCS values of 3.51MPa, 3.81 MPa, 4.01 MPa, 4.12 MPa, 3.4 MPa, the required C for the cement stabilized Soil A is 3.81%, 4.17%, 4.40%, 4.12% and 3.77%, respectively. The cement-NRL stabilized Soil A on the other hand achieves the target UCS values at C = 3% by adding NRL at NRL replacement ratios of 10%, 15%, 20%, 25%, and 30%, respectively. The reduction in CO_2-e emission was found to be 19.70%, 27.36%, 30.72%, 19.18%, and 6.24% for NRL replacement ratios of 10%, 15%, 20%, 25%, and 30%, respectively.

This research study indicates that the NRL is an environmentally friendly additive, which has a potential in initial strength and durability improvement. The application of NRL for cement stabilized base course could promote the usage of natural rubber in Southeast Asia countries for development of sustainable road pavement.

4.6 CONCLUSIONS

This research ascertains the usage of natural rubber latex (NRL) as a green additive in cement stabilized base course. The NRL can improve both short- and long-term performance. The following conclusions can be drawn from this research study:

1. The cement-NRL stabilized samples have higher UCS than the cement stabilized samples for all cement contents and NRL replacement ratios tested. The strength development is due to the composite between cement hydration and the latex film formation, which served to be the reinforcement. The highest UCS value is found at an optimum NRL replacement ratio, which is 20%, 15%, and 10% for 3%, 5%, and 7% cement, respectively.

2. The UCS values are lower for the higher DRC at the same cement contents and NRL replacement ratios. The higher DRC is accompanied by the higher non-rubber substance, causing more premature coagulation and cement retardation.

3. The optimum liquid content is governed by fine content. The higher the fines content results in the optimum liquid content due to higher water holding capacity. As such, the soil with higher fines content has lower UCS than that with lower fine content at the same cement content and NRL replacement ratio.

4. The lowest weight loss is found at the optimum NRL replacement ratios for all 3 types of NRL and both Soil A and Soil B. The excess NRL content significantly causes the retardation of cement hydration, thereafter the bonding strength of the stabilized samples reduces. The lowest weight loss is found at NRL Type 1 (the lowest DRC), followed by NRL Type 2 and NRL Type 3.

5. The $UCS_{(w-d)}$ of cement-NRL stabilized soil is higher than that of cement stabilized soil and has lower rate of strength degradation. Based on the analysis of test results, the $UCS_{(w-d)}$ predictive equation was proposed for various NRL replacement ratios, cement contents and soil types in term of UCS_0, which is simply obtained from the conventional test. The equation is useful of geotechnical and pavement engineers and practitioner.

6. Based on the strength test results and carbon footprint analysis, NRL is proved as a green additive in cement stabilized soil. It helps reduce the input of cement to attain high target UCS(w-d) and hence the recursion in carbon footprint. With the same target of UCS_0 = 4.4 MPa, the cement-NRL stabilized soil has 30.7 % lower carbon footprint than the cement stabilized soil.

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CHAPTER V

IMPROVEMENT OF TENSILE PROPERTIES OF CEMENT STABILIZED SOIL USING NATURAL RUBBER LATEX

5.1 Statement of problem

The major transportation in rural areas in various developed and developing countries, including Thailand are usually by unpaved roads. According to the annual report of the Thailand Office of Transport and Traffic Policy and Planning 2018 (Thailand Office of Transport and Traffic Policy and Planning 2018), there have been more than 4000 kilometers of unpaved roads, and they tend to increase every year with a rate approximately of 15 km/year.

The unpaved roads in the undeveloped regions serve as a major transportation network, which could impel economic basis development and income distribution for the rural population. Furthermore, the establishment of a well-connected system of rural transportation can enhance the opportunities for local residents in undeveloped districts to access utilities, educational, agricultural product transportation, and medical service systems (Starcher et al. 2018).

The primary objectives of the unpaved roads have intended to respond to low transportation volume. Unpaved roads are usually therefore constructed from the local materials. However, the local materials often exhibit deficient quality to achieve minimum construction standards (Steyn et al. 2014). Several problems on unpaved roads as a result of construction with low quality materials have often been found (So lanky and Saman, 2011 and 2014; Tang et al. 2014, Starcher et al. 2018, and Li et al. 2017). The unpaved roads constructed with high plasticity, low bearing capacity and high abrasion soils usually fail by the permanent deformation or erosion due to mechanical and environmental stresses (Steyn et al. 2014 and Lv et al., 2019). The repeated traffic loading is typically generated the vertical and horizontal stresses, thereafter the tensile stress occurs at the bottom half of the unpaved surface layer (Kavussi and Modarres 2010).

In order to maintain the serviceability of unpaved roads, the frequent maintenance is required. The compensation of particle loss by the additional materials, and the structural restoration by the reconstructing with the same materials have usually been practiced. This maintenance is uneconomical and unsustainable solution. The demand for maintenance is mainly dependent upon the number of transportation users (Starcher et al. 2018, Bushman et al. 2005).

The cement stabilization has extensively been applied worldwide in road infrastructure since 1915. Thailand's Department of Highways has applied this technique since 1965 to improve the load capacity of local low quality materials for both unpaved and paved roads (Zhang and Tao 2008, Horpibulsuk et al. 2006).

The cement stabilization can improve the resistance to permanent deformation, environmental resistance, durability and water permeability of unpaved base material (Baghini et al. 2016, Bellezza and Fratalocchi 2006, Suddeepong et al. 2018, Horpibulsuk et al. 2010, and Horpibulsuk et al. 2012) due to the cementation bonding (Horpibulsuk et al. 2005).

The major failure of cement stabilized soil is attributed to shrinkage crack, erosion of fine grains, and fatigue failure. The shrinkage and erosion can be overcome by using suitable materials and binders in accordance with the local and international standards of stabilized materials selection (Biswal et al. 2020). The cement stabilization effectively improved resilient modulus and the resistance to permanent deformation of the unpaved material, however, the potential of cement stabilized materials to sustain the repeated tensile loading decreases (Gnanendran and Piratheepan 2009 and Kim et al. 2012). The higher cement content caused the higher brittleness and the reduction in tensile fatigue life at a large strain level; hence, the sudden failure occurs with crack initiation (Kavussi and Modarres 2010, Salomon and Newcomb 2000, Suleiman 2002, and Brown and Needham 2000 and Chen et al., 2011).

In order to mitigate the shortcoming in the premature of cement stabilized materials, the combined applications of cement and synthetic polymer additives have been praised as an effective solution (Baghini et al. 2014). The prominent features of synthetic polymer typically involve internal film formation within the microstructures of material. The flexural strength improvement is accompanied by higher elastic behavior as a result of the film formation of the polymer matrix (Yaowarat et al., 2019).

Consequently, flexibility and durability are evidently enhanced by means of adhesive strength development (Baghini et al. 2014, Marto et al. 2014, Onyejekwe and Ghataora 2015, and Tingle et al. 2007). Moreover, the frequent maintenance problem of the unpaved system can be effectively solved by the participation of polymer additives. The major problems in unpaved roads such as particle loss, permanent deformation, and dust generations can also be mitigated with the utilization of an appropriated type of polymer (Steyn et al. 2014, and Starcher et al. 2018).

Likewise, natural rubber latex (NRL), a plant product with the high tensile and impact strengths and high elastic and elongation properties (Sanhawong et al. 2017), can be used as an environmental-friendly additive alternative to synthetic polymers. The NRL consists of the solid and liquid composition, combined into colloidal substance. The polymer concentrations by total colloidal weight are between 25 to 40 percent. The polymer components consist of approximately 94% rubber hydrocarbon and 6% non-rubber substances (Vo and Plank 2018 and Sakdapipanich 2007). Biological and morphological evidence revealed that spherical molecules of NRL, the estimated particle size in the range of 0.1 - 2.0 micrometers, are composed of carbon content over 90%, surrounded by the non-rubber compound with protein and phospholipids layers by random packing arrangement (Nawamawat et al. 2011, Herculano et al. 2011, and Rathnayake et al. 2012). Although the non-rubber substance appeared to be only a small amount, these components caused multifarious undesirable properties such as the coagulation to cementing reaction (Nagaraj et al. 1988). In order to overcome this problem, the deproteinization method has been introduced to eliminate the bonding of non-rubber constituents. The surfactant sodium dodecyl sulphate (SDS) has been applied as a chemical agent.

The non-rubber bonding layers are consequently destroyed. The SDS replaces the non-rubber layers by means of covering the latex particles to prevent the coagulation and improve workability (Vo and Plank 2018).

The coalesce film of NRL has the potential to serve as a reinforcing material. The natural film of NRL within the cementitious matrix empowered the sample's cohesive strength of cement stabilized soil, consequently compressive and tensile strengths are surprisingly improved (Buritatun et al., 2020; Muhammad et al. 2012, and Nagaraj et al. 1988). In addition, resistance to environmental corrosion and thermal degradation can effectively be improved (Muhammad and Ismail 2012, and Muhammad et al. 2011).

Thailand is the largest natural rubber exporting country in the world with approximately 38.82% of the rubber world export (Thailand Rubber Authority, 2019). The combined usage of NRL and cement can be the sustainable innovation to enhance tensile properties for unpaved roads. To the best of the authors' knowledge, there has been no research undertaken to date on the application of NRL on cement stabilized soil to improve the tensile and fatigue characteristics of unpaved stabilized material. Indirect tensile strength fatigue test, an effective method to simulate the reliable tensile performance of stabilized materials (Gnanendran and Piratheepan 2008, Gnanendran and Piratheepan 2009, Solanki and Zaman 2011, and Solanki and Zaman 2014), was conducted on cement stabilized soil with various NRL replacement ratios and cement contents. The outcome of this research will promote the usage of NRL as an alternative additive in cement stabilized unpaved roads in Thailand and other Southeast Asia countries.

5.2 Materials

5.2.1 Soil Sample

The lateritic soil, the regular pavement materials in the tropical region, was used in this research. Three lateritic soil samples from different sources (Soil A, Soil B, and Soil C) were selected. Soil A and Soil B were collected from a borrow pit in Nakhon Ratchasima province while Soil C was from Saraburi province, Thailand.

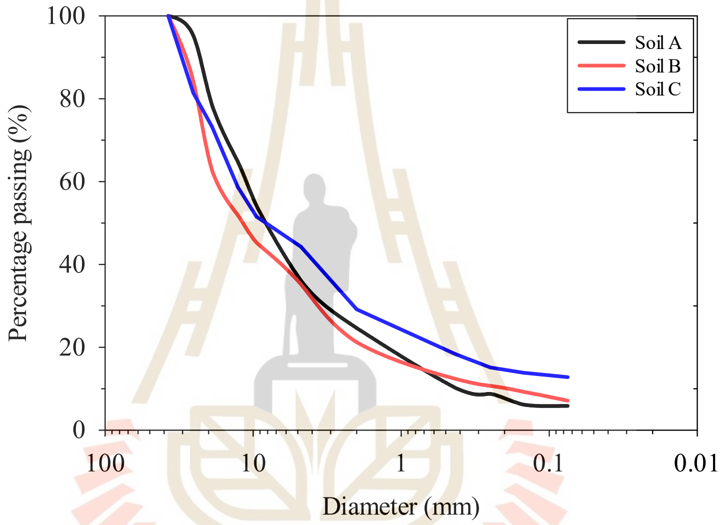

Figure 5.1 Particle size distributions of studied soils

The three soils had entirely different physical and engineering properties. According to the Unified Classification System (USCS), Soil A, Soil B, and Soil C were classified as well-graded gravel with clay (GW-GC), poorly-graded gravel with clay (GP-GC) and clayey gravel (GC), respectively. The grain size distribution curves for the three soil samples are illustrated in **Figure 1** and basic engineering properties are summarized in **Table 1**. These studied soils did not meet the minimum requirements in accordance with the standard of materials selection for unpaved roads of the Department of Rural Roads, Thailand (DRR206-2545). The California bearing ratios of all samples were lower than the requirement of 30%. As such, the three soils are required to stabilize with cement to be unpaved stabilized materials whose geotechnical properties met the standard of stabilized materials of the Department of Highways, Thailand (DH-S204/2532).

5.2.2 Cement

The Portland cement type I is the common cementing agent for stabilized pavement applications worldwide including Thailand. It was therefore selected to stabilize all studied soils. The properties of Portland cement are demonstrated in **Table 5.2**. The compressive strength measurement at 7-day and 28-day were 27.4 MPa and 32.6 MPa, respectively.

5.2.3 Natural Rubber Latex (NRL)

The natural rubber latex (NRL) was supplied from the Rubber Authority of Thailand. This NRL was treated with sodium dodecyl sulphate (SDS), zinc 2-mercaptobenzothiazole (ZMBT), zinc oxide, calcium carbonate, and sulphur substance to improve the workability and desired properties of NRL. The studied NRL consisted of 33.06% total solid contents by total weight, which composed of 30.79% dry rubber content (DRC) by total weight. The studied NRL was categorized as the low-class DRC (DRC < 31% by total weight) (Muhammad et al. 2012). After the treatment process, the NRL became the water and water-soluble substances in the colloidal liquid (Vo and Plank 2018). Since the NRL is in liquid state, the input of NRL as a replacement ratio by total liquid content was convenient for fieldwork.

Table 5.1 Engineering Basic Properties of Soil

Sample Properties	**Soil sample A**	**Soil sample B**	**Soil sample C**	**Standard for unpaved materials (DRR-206/2545)**	**Standard for stabilized materials (DH-S204/2532)**
	Values				
Largest particle size	25.4	37.5	37.5	≤ 50	≤ 50
(mm)	33	42	46	≤ 60	≤ 60
Los Angeles abrasion (%)	22	28	29	≤ 35	≤ 40
Liquid limit LL (%)			14	-	
Plastic limit PL (%)	10	14			-
Plasticity index PI (%)	12	14	15	4 - 11	≤ 15
Specific Gravity (G_s)	2.76	2.74	2.71	-	-
Maximum dry density under MOD energy (kN/m^3)	20.88	19.86	18.94	-	-
Optimum water content under MOD energy (%)	8.09	9.24	10.07	-	-
Maximum dry density under STD energy	-	18.14	-	-	-
(kN/m^3)	-	12.47	-	-	-
Optimum water content under STD energy (%)					
California bearing ratio (%)	18.24	13.01	10.65	≥ 30	-

Table 5.2 Chemical Compositions of Cement

Composition	**Value (%)**
Silicon dioxide (SiO_2)	20.7
Sulphur oxide (SO_2)	4.8
Ferric oxide (Fe_2O_3)	3.1
Aluminium oxide (Al_2O_3)	4.7
Calcium oxide (CaO)	65.3
Magnesium oxide (MgO)	2.8
Loss on ignition (LOI)	0.9

5.3 Experimental procedures

5.3.1 Preparation and testing condition

According to the ACI 230.1R-09 report (ACI 230, 2009), the typical cement requirement for the cement stabilized granular soils is recommended to be between 3% to 9% by total weight of dried soils. Department of Highways, Thailand specifies the minimum 7-day compressive strength to be 1.724 and 2.413 MPa for low and high traffic roads, respectively (DH-S204/2532). The cement contents of 3%, 5%, and 7% (C = 3%, 5%, and 7%) were selected for this research, which are the common practical range in Thailand. The soil samples were sieved in order to remove the coarser aggregates than 19 mm and were then air-dried. The soil and cement were thoroughly mixed by hand to have a uniform mixture according to ASTM D1632. The soil-cement mixtures were subsequently mixed with liquid admixture (water and NRL) using water droplets. The NRL replacement ratios was varied: 10%, 15%, 20%, and 30% by weight of water. Samples were compacted in a metallic mold with dimensions of 101.60 mm diameter and 116.8 mm height to determine maximum dry density (MDD) and optimum of liquid content (OLC).

Horpibulsuk et al. (2010) revealed that besides the curing time and cement content, the engineering properties of cement stabilized soil were affected by the molding water content and compaction energy. The effect of molding water content (0.8 OLC, OLC and 1.2 OLC) and compaction energy (standard and modified Proctor energy) on ITS was then investigated by Soil B at different cements and NRL contents.

5.3.3 Unconfined Compressive Strength (UCS)

The UCS test was carried out on the cement-NRL stabilized samples at the various mixed ingredients to evaluate the impact of NRL replacement ratio on compressive strength. The samples were compacted in a metallic mold with dimensions of 101.60 mm diameter and 116.8 mm height by using a static compression machine to attain MDD at OLC. The UCS test was conducted in accordance with ASTM D1633 standard by using a universal testing machine with an automatic data recorder at a rate of 1 mm/min.

5.3.4 Indirect Tensile Strength (ITS)

The ITS test is an effective method to evaluate the tensile strength of cement stabilized soil (Gnanendran and Piratheepan, 2008) in accordance with ASTM D6931 for pavement engineering design. The samples were compacted in a metallic mold with dimensions of 101.60 mm diameter and 65.00 mm height by using a static compression machine to attain the target dry densities and liquid contents (0.8OLC, OLC and 1.2OLC). The cement stabilized samples with and without NRL were installed in the testing equipment with a loading strip of 19 mm wide and 125 mm long. The samples were then subjected the static vertical stress at the deformation rate of 1 mm/min using a universal testing machine with an automatic data recorder. The ultimate ITS was calculated in accordance with the elastic theoretical approach by the following equation.

$$IDT = \frac{2P}{\pi dt} \quad (1)$$

where P is the is a maximum load (N), t is the sample thickness (mm), and d is the sample diameter (mm)

5.3.4 Indirect Tensile Fatigue (ITF)

The indirect tensile fatigue (ITF) test was carried out to characterize the fatigue behavior of cement-NRL stabilized soil in accordance with the EN 12697-24 standard. The dimension and sample preparation of the ITF samples were the same as those of the ITS samples. In order to simulate low traffic loading scenario for unpaved road, the haversine load pulse with a low frequency of 0.66 Hz was applied as suggested by Kavussi and Modarres (2010). Even though the rural road is typically designed for the low traffic volume; nevertheless, the transportation of agriculture, livestock, and local industry products usually involve with a heavy truck portage. Consequently, the samples were subjected to a stress level of 30%, 50%, and 70% of the ultimate ITS of samples without NRL. Throughout the test, horizontal deformations were measured by LVDT and automatically recorded by a related software.

According to EN 12697-24, fatigue life is defined as the total number of loading cycles needed to destroy the sample. The tensile strain at the center of the sample is calculated with the following equation.

$$\varepsilon_0 = \left(\frac{2\Delta H}{d}\right) \times \left(\frac{1+3\nu}{4+\pi\nu-\pi}\right) \tag{2}$$

By assuming that the Poisson's ratio (ν) is equal to 0.35, Equation (2) then becomes:

$$\varepsilon_0 = 2.1\frac{\Delta H}{d} \tag{3}$$

where ε_0 is the tensile strain at the center of the sample (μ_ε), ΔH is the measured horizontal deformation (mm), and *d* is the sample diameter (mm). Similarly, the plastic tensile strain at the center of the sample is calculated with the following equation:

$$\varepsilon_p = 2.1\frac{\Delta p}{d} \tag{4}$$

where ε_p is the tensile plastic strain at zone 2 at the center of the sample ($\mu\varepsilon$), Δp is the initial plastic deformation (mm), and *d* is the sample diameter (mm).

All of the tested samples along with the molds were wrapped with vinyl sheet for 24 hours. Subsequently, they were demolded, wrapped with vinyl sheet and stored in a 95% relative humidity room at 25 °C temperature until the unconfined compression strength (UCS), indirect tensile strength (ITS) and indirect tensile fatigue (ITF) tests at 7 days of curing. In order to ensure the reliability of the test result, at least three samples were prepared for each mix. The indirect tensile strength (ITS) for all studied soils and indirect tensile fatigue (ITF) for Soil A and Soil C were measured.

5.4 RESULTS AND DISCUSSION

5.4.1 Unconfined Compressive Strength (UCS)

Figure 5.2 illustrates the UCS versus NRL replacement ratio relationship at different cement contents for Soil A, Soil B, and Soil C. The solid line in **Figure 5.2** represents the minimum UCS requirement for unpaved cement-stabilized materials according to DH-S204/2532 standard. The UCS of cement stabilized soils is enhanced by the addition of NRL for all cement contents. The dashed lines represent the trendline for Soil C at C = 3%, 5% and 7%. It is noted that Soil A and Soil B also present the similar trend to Soil C but only with different magnitudes. The optimum NRL ratio providing the highest UCS is 20%, 15%, and 10% for C = 3%, 5%, and 7%, respectively for all the studied soils.

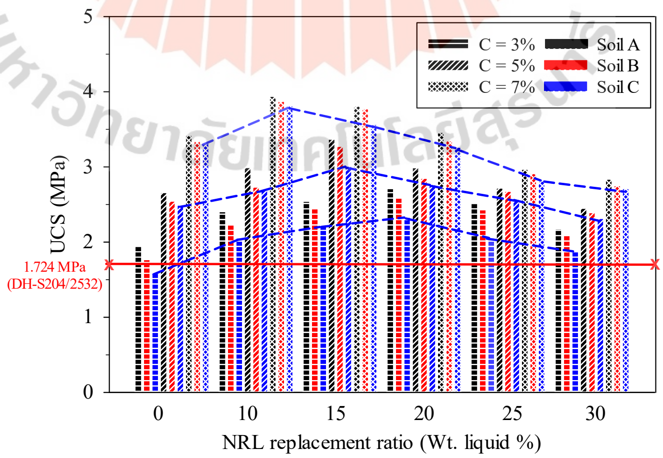

FIGURE 5.2 Unconfined compressive strength for different cement contents and NRL replacement ratios of soil A soil B and soil C.

The NRL films can infiltrate and reduce void space within the soil-cement matrixes and also enhance the interparticle forces (Buritatun et al. 2020). Beyond the optimum NRL ratio, the UCS decreases with the increased NRL replacement ratio. The excessive NRL content causes the loose microstructures, resulted from the decreased density (Buritatun et al. 2020). For a given cement content and NRL replacement ratio, Soil A has the highest UCS and is followed by Soil B and Soil C. In other words, the UCS decreases as the increase in fine content.

5.4.2 Indirect Tensile Strength (ITS)

The ITS values for 3%, 5%, and 7% cement stabilized Soil A, Soil B, and Soil C at various NRL replacement ratios are illustrated in **Figure 5.3**. In case of the cement stabilized soils (without NRL), the higher cement content is associated with the higher ITS as a result of the higher cementitious products. In other words, the cement matrix within the compacted soil strengthens inter-particle bonding strength (Horpibulsuk et al. 2010).

It is noted from **Figures 5.3** that the soil plasticity affects the ITS similar to UCS. For a particular cement content, Soil C (highest LL) exhibited the lowest ITS, followed by Soil B (medium LL) and Soil A (lowest LL). The higher plasticity causes the higher OLC, resulting in the higher water to cement ratio and the lower strength for the same input of cement (Horpibulsuk et al. 2005 and Sudla et al. 2019).

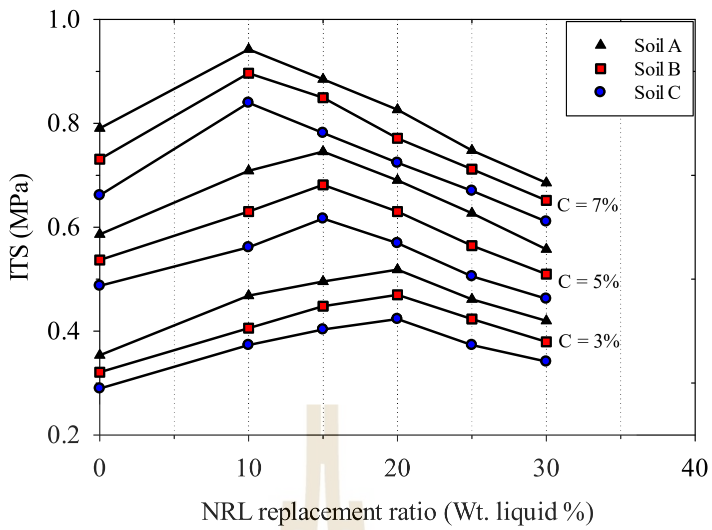

FIGURE 5.3 Indirect tensile strength for different cement contents and NRL replacement ratios of soil A soil B and soil C.

The ITS of cement-NRL stabilized soils is primarily influenced by the NRL replacement ratio. For all the studied soils, ITS increases with increasing the NRL replacement ratio up to the highest value at the optimum NRL replacement ratio. Beyond this optimum NRL replacement ratio, the ITS decreases. The optimum NRL replacement ratio depends upon the cement content and is equal to 20%, 15%, and 10% at C = 3%, 5%, and 7%, respectively. In other words, the optimum NRL replacement ratio decreased with the increase in cement content. The highest ITS for C = 3% (at 20% NRL), 5% (at 15% NRL), and 7% (at 10% NRL) is 0.52 MPa, 0.75 MPa, and 0.94 MPa for Soil A and 0.47 MPa, 0.68 MPa, and 0.89 MPa for Soil B and 0.42 MPa, 0.62 MPa, and 0.84 MPa for Soil C, respectively.

The ITS improvement is resulted from the NRL film formation within the compacted matrix after the liquid substances evaporate away, and the films connected soil-cement particles (Vo and Plank 2018 and Buritatun et al. 2020).

Therefore, the soil-cement cohesive matrix is improved by means of reinforcements from NRL films formation with the denser structures. The excess NRL replacement causes the coagulation between cement and NRL film (Nagaraj et al. 1988). In addition, the excess NRL replacement induces the high amount of non-rubber substance such as protein and phospholipid, especially the deleterious composition of acid and bacteria (Muhammad et al. 2011), which retards the hydration process (Buritatun et al. 2020).

The ITS is contributed from both cementitious products and NRL films. Though NRL films improves the soil cohesion (tension), they retard the hydration. At low cement content (C = 3%), the cementitious products slightly affect the ITS development, and the effect of NRL films on cohesion improvement is more dominant than the retardant effect (Buritatun et al. 2020). At the high cement content (C = 5% and C = 7%), the optimum NRL replacement ratio decreases as the increase in cement content due to the retardant effect of NRL (Buritatun et al. 2020). As such, the optimum NRL replacement ratio decreases with increasing the cement content. At the maximum NRL replacement ratio (NRL = 30%), the ITS of 3%C + 30% NRL stabilized soil still remains higher than that 3% C stabilized soils (without NRL), whereas the ITS values of 5%C + 30% NRL stabilized soils and 7%C + 30% NRL stabilized soils are lower than ITS values of 5%C stabilized soil and 7%C stabilized soil, respectively (**Figure 5.3**).

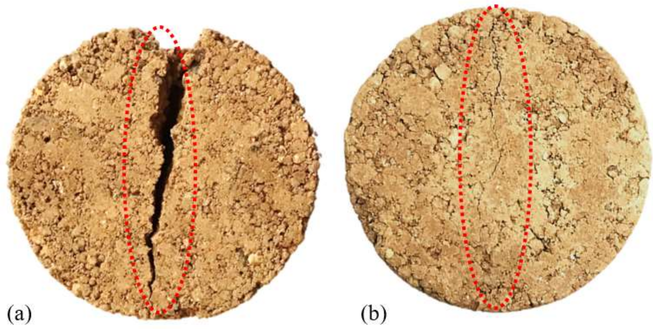

FIGURE 5.4 Failure characteristics of (a) cement stabilized soil A and (b) 20% NRL-cement stabilized soil A at C = 3% samples.

In addition to the ITS improvement, the failure mode is also improved as seen in **Figure 5.4**. Without NRL, the single distinct crack with sudden split failure is clearly observed after the peak load. Whereas several small cracks are detected on the cement-NRL stabilized sample. The tensile stress can be transferred to the whole parts of the sample through the NRL films. As such, the multiple cracks on different parts of the sample develop and the cement-NRL stabilized sample can carry higher tensile stress than the cement stabilized sample.

Figure 5.5 illustrates the influences of liquid content on ITS at different NRL replacement ratios and cement contents. The stabilized samples at 1.2 OLC and 0.8 OLC demonstrate lower ITS values than those at OLC for various NRL replacement ratios. On the dry side of optimum (0.8 OLC), the ITS is the lowest for all cement contents and NRL replacement ratios (**Figure 5.5)**.

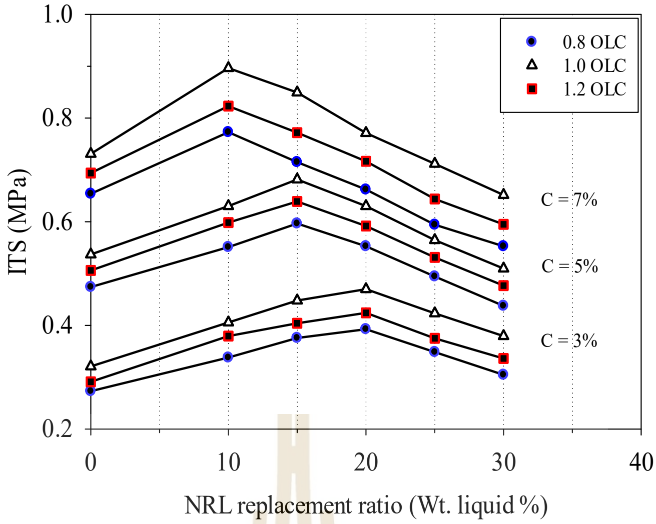

FIGURE 5.5 Indirect tensile strength for different cement contents and NRL replacement ratios of soil B at 0.8 OLC, 1.0 OLC and 1.2 OLC.

This is because the liquid is not sufficient to lubricate the soil particles into the densely packed state under a particular effort energy (Horpibulsuk et al. 2006 and Chinkulkiniwat and Horppibulsuk, 2012). In addition, the inadequate liquid content generates a low degree of hydration (Horpibulsuk et al. 2006). On the wet side of optimum (1.2 OLC), the ITS values are higher than those at 0.8 OLC due to the sufficient liquid for hydration. However, the ITS values are lower when compared to those at OLC (**Figure 5.5)**. This is because the high liquid content of 1.2 OLC causes the reduced density and loose structures. Moreover, with the high liquid content (high NRL content), the remained non-rubber component increases and retards the cement hydration.

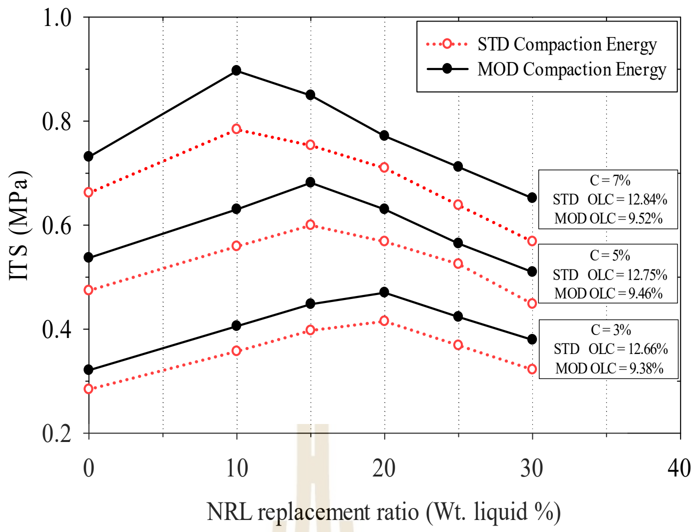

FIGURE 5.6 Indirect tensile strength for different cement contents and NRL replacement ratios of soil B under STD and MOD compacted energy.

Figure 5.6 presents the 7-day ITS versus NRL replacement ratio of the cement-NRL stabilized samples at C = 3%, 5%, and 7% under standard (STD) and modified (MOD) Proctor compaction energy. The higher compacted energy (MOD) leads to the higher ITS due to the denser compacted matrix and lower OLC. The OLC values are 12.66%, 12.75%, and 12.84% for STD while are 9.38%, 9.46%, and 9.52% for MOD at C = 3%, 5% and 7%, respectively. It is evident that the compaction energy does not affect the NRL replacement ratio at a given cement content. The lower OLC causes a lower non-rubber component and water to cement ratio at the same cement content; hence higher cementitious products.

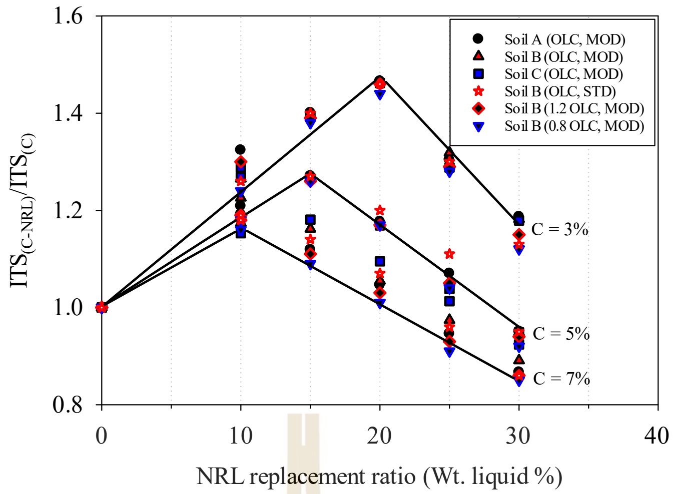

FIGURE 5.7 Relationship between $UCS_{(C\text{-}NRL)}/UCS_{(C)}$ and NRL replacement ratios for Soil A and Soil B at 3% cement content, 5% cement content, and 7% cement content.

The normalized strength is typically used to describe influence factors on the strength development compared to initial strength (Neramitkornburi et al. 2015, Suddeepong et al. 2018, and Kampala et al. 2014). It is thus employed to investigate the role of NRL replacement ratio, soil property, liquid content and the compaction energy on ITS of cement-NRL stabilized soils. The normalized $ITS_{(C\text{-}NRL)}/ITS_{(C)}$ (ratio of ITS values of cement-NRL stabilized soils to ITS values of cement stabilized soils) against NRL replacement ratio was plotted and is shown in **Figure 5.7** for Soil A, Soil B and Soil C at C = 3%, 5% and 7%. The normalized $ITS_{(C\text{-}NRL)}/ITS_{(C)}$ versus NRL replacement ratio plot is only dependent upon the cement content, irrespective of NRL replacement ratio, soil property, liquid content and the compaction energy.

The maximum normalized $ITS_{(C\text{-}NRL)}/ITS_{(C)}$ values is found at NRL = 10%, 15% and 20% for C = 7%, 5% and 3%, respectively, which is approximately 1.46, 1.27 and 1.20 for 3%, 5% and 7%, respectively. This relationship is similar to the normalized compressive strength of cement-NRL stabilized soils (Buritatun et al. 2020).

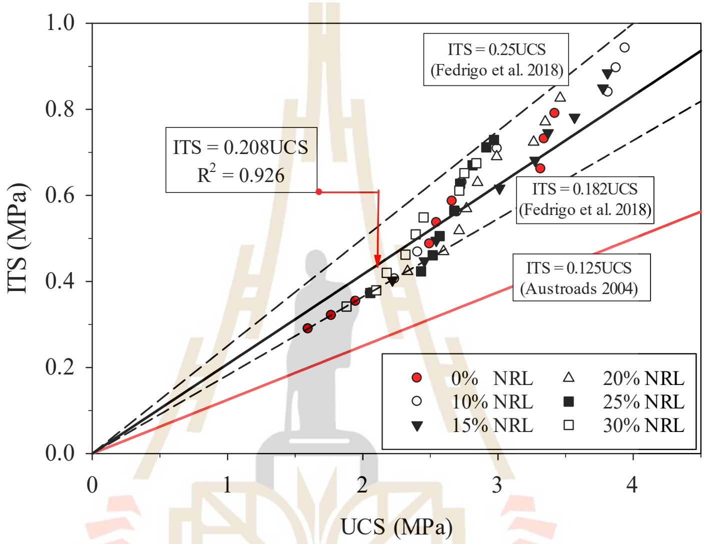

FIGURE 5.8 Relationship between ITS and UCS for cement stabilized Soil A, Soil B and Soil C with and without NRL at C = 3%, C = 5% and C =7% for different NRL replacement ratios.

Based on the previous (Buritatun et al., 2020) and present research, both normalized UCS and normalized ITS of cement-NRL stabilized soils are controlled by the same influence factor (cement content). It is therefore logical to develop the relationship between ITS and UCS for cement-NRL stabilized soils as shown in **Figure 5.8**.

The ITS and UCS relationship was then developed based on a regression analysis and is presented as follows:

$$ITS = 0.208(UCS) \quad (5)$$

where the degree of correlation, R^2 is very high of 0.926. Austroads (2004) suggests that the ITS of the cement stabilized materials is between 0.125UCS and 0.10UCS. While Fedrigo et al. (2018) proposed ITS = (0.15 - 0.25) UCS. It is evident that the test data of the studied soils are close to the limits proposed by Fedrigo et al. (2018). The development of this relationship is on sound principles based on the data with NRL replacement ratios = 10% to 30%, DRC approximately 31%, C = 3%, 5% and 7%, LL < 40%, and PI < 15%. This relationship is useful as the ITS can be approximated from the UCS, which is simply obtained from laboratory test.

5.4.3 Indirect Tensile Fatigue (ITF)

Figures 5.9 and **5.10** illustrate the relationship between the number of cycles versus horizontal deformation of the cement and cement-NRL stabilized Soil C at C = 3% to 7% for different NRL replacement ratios at 70% and 30% stress levels. The horizontal deformation behavior against the increased number of cycles is divided into three zones for all samples. In the first zone, the large deformation happens at a small number of cycles due to the occurrence of plastic deformation. In the second zone, the deformation is linearly proportional to the increased number of cycles. Throughout the loading period, the microcracks are formed and gradually developed. In the third zone, the accumulated microcracks ultimately cause complete splitting failure (Modarres and Alinia Bengar 2019 and Kavussi and Modarres 2010).

Figure 5.9d shows a method to determine fatigue life (NF) and initial deformation at zone 2 (Δp). The initial deformation at zone 2 (Δp) is defined as the intersect of the straight lines extending from linear portion in zone 1 and zone 2. The NF is the number of cycles at the breakage of the sample.

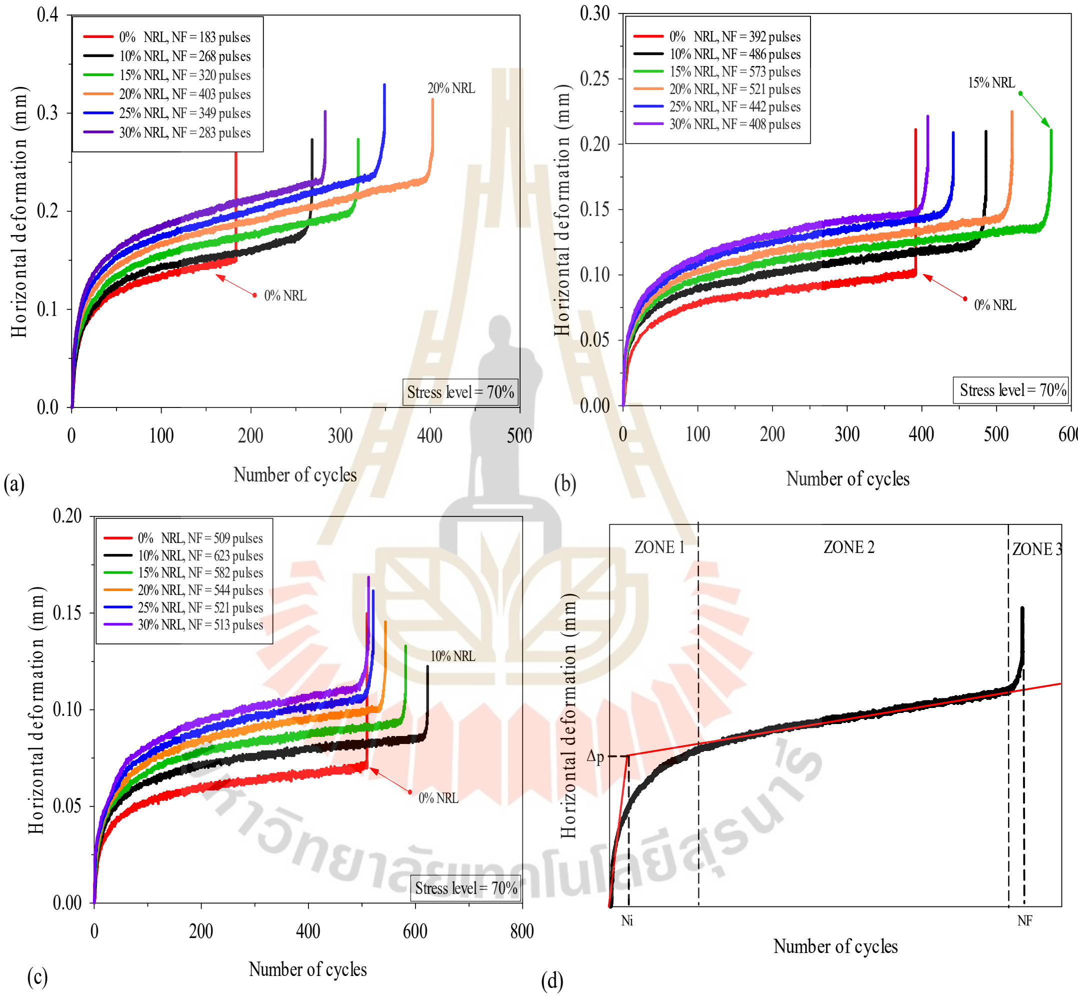

FIGURE 5.9 Relationship between number of cycles and horizontal deformation of cement stabilized Soil C for (a) C=3%, (b) C=5%, and (c) C=7% at different NRL replacement ratios at 70% stress level, and (d) schematic plot.

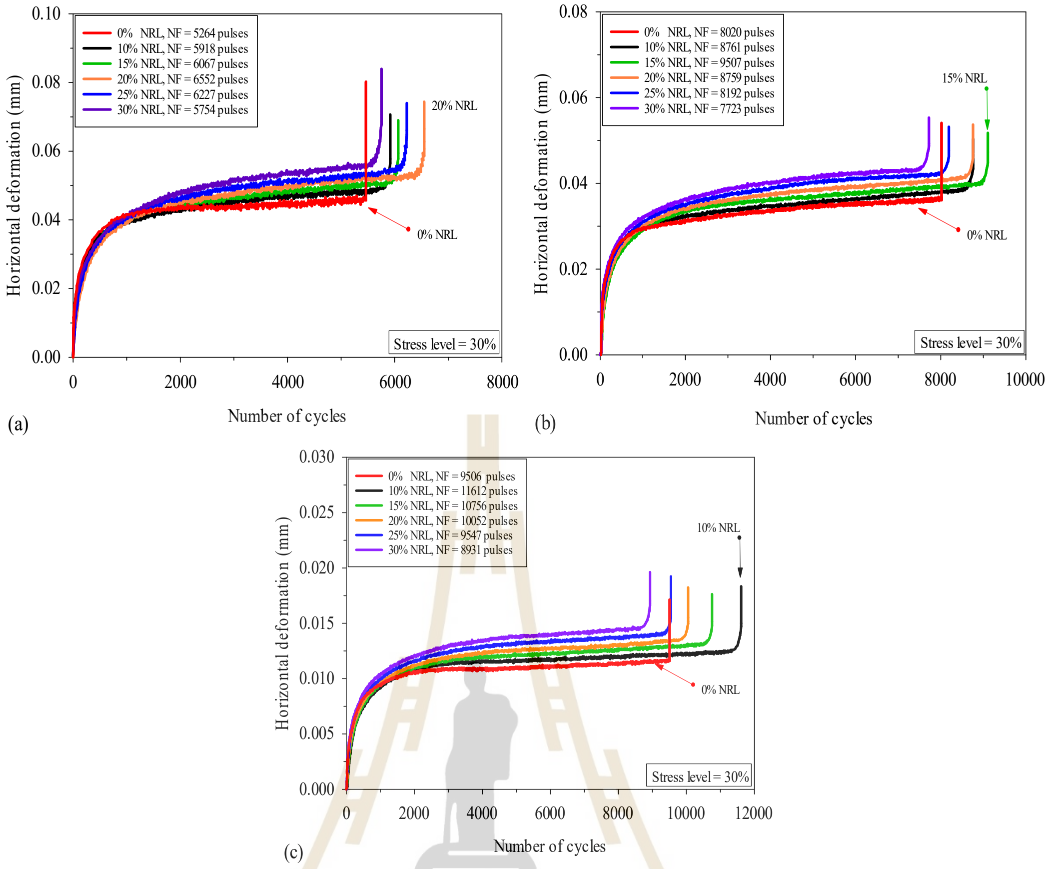

FIGURE 5.10 Relationship between number of cycles and horizontal deformation of cement stabilized Soil C for (a) C=3%, (b) C=5%, and (c) C=7% at different NRL replacement ratios at 30% stress level.

The brittle behavior is observed for cement stabilized samples as indicated by the sudden failure at the transition between the second and third zones for both 70% and 30% stress levels. The high cement content causes the rapid cracking failure, particularly under high stress levels (Kavussi and Modarres 2010). The NF of cement-NRL stabilized samples increases with increasing the NRL replacement ratio and reaches the maximum value at the optimum NRL replacement ratio. Similar to the indirect tensile strength test results, the optimum NRL replacement ratio for NF reduces with the input of cement and is equal to 20%, 15%

and 10% for C = 3%, 5% and 7%, respectively for all stress levels. For all C, at the same number of cycles, the cement-NRL stabilized samples exhibits larger deformation than the cement stabilized samples at large stress ratio of 70%. The same is not true of the low stress level. At 30% stress level, the cement-NRL stabilized samples have similar deformation to the cement stabilized samples in zone 1 and become higher in zone 2.

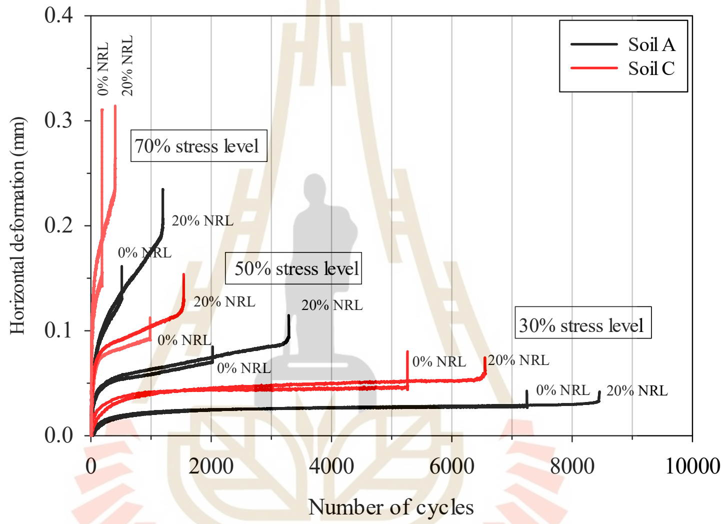

FIGURE 5.11 Relationship between number of cycles and horizontal deformation of cement stabilized Soil A and Soil C for C=3%, 0% and 20% NRL replacement ratios at 30%, 50%, and 70% stress level.

The comparison of the relationship between the number of cycles and horizontal deformation for cement and cement-NRL stabilized samples at C = 3% and NRL replacement ratio = 20% (optimum) for Soil A and Soil C at 30%, 50%, and 70% stress levels is presented in **Figure 5.11.** The NF and deformation behavior depend on the imposed stress level. Due to higher OLC and lower MDD, Soil C exhibits a higher total and plastic deformations and lower fatigue life than Soil A at the same stress level for both samples with and without NRL.

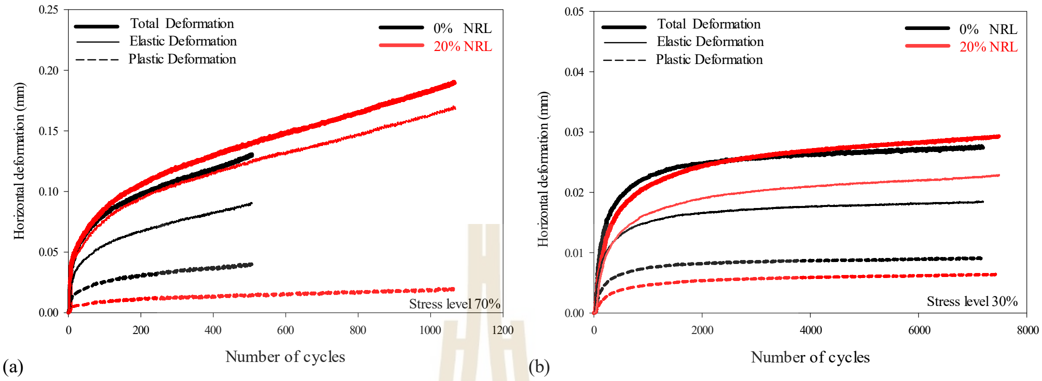

FIGURE 5.12 Total, elastic, and plastic deformation in zone 1 and zone 2 for cement stabilized Soil A at C=3%, 0%, and 20% NRL replacement ratio at (a) 70% and (b) 30% stress levels.

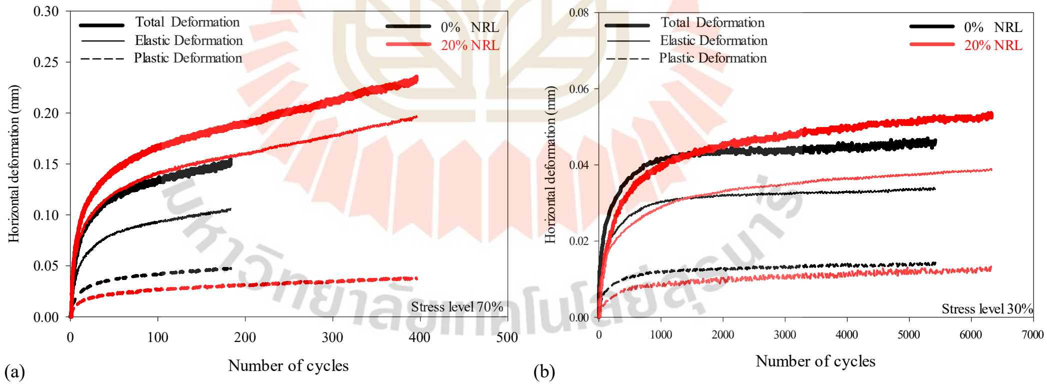

FIGURE 5.13 Total, elastic, and plastic deformation in zone 1 and zone 2 for cement stabilized Soil at C=3%, 0%, and 20% NRL replacement ratio at (a) 70% and (b) 30% stress levels.

The total deformation for each loading cycle is the sum of elastic (recoverable) and plastic deformation. The accumulation of plastic deformation results in excessive deformation, and subsequently the permanent deformation (rutting failure) (Sobhan and Das 2007). **Figures 5.12** and **5.13** present the accumulated total, elastic and plastic deformations prior to failure (within zone1 and zone 2) of cement and cement-NRL stabilized Soil A and Soil C for C = 3% at 70% and 30% stress levels. The plastic deformation determined by the unrecoverable deformation, while elastic deformation is defined by the differences between total and plastic deformation.

Although the cement-NRL stabilized samples exhibits higher total deformation, the plastic deformation is lower and the elastic deformation is higher when compared to the cement stabilized samples for both Soil A and Soil C. At the low and high stress levels, the cement-NRL stabilized samples exhibit remarkably lower plastic deformation than the cement stabilized soil. The influence of stress level can be clearly observed in that the difference in accumulated plastic strain of samples with and without NRL is large at the high stress level. It is found that the elastic deformation of cement-NRL stabilized Soil C is approximately 79% and 77% of total deformation for 30% and 70% stress level, respectively. Whereas the elastic deformation of cement stabilized Soil A is lower of approximately 72% and 69% of total deformation for 30% and 70% stress level, respectively.

The plastic strain is a measure of stress-induced damage contributing to fatigue failure (Sobhan and Das 2007). As such, the relationship between stress level versus NF and initial plastic tensile strain (ε_p) at zone 2 (plastic deformation (Δp) referenced to **Figure 5.9d**) for C = 3%, 5%, and 7% under stress levels of 30%, 50% and 70% was plotted and is presented in **Figures 5.14** and **5.15** for Soil A and Soil C, respectively with various NRL replacement ratios.

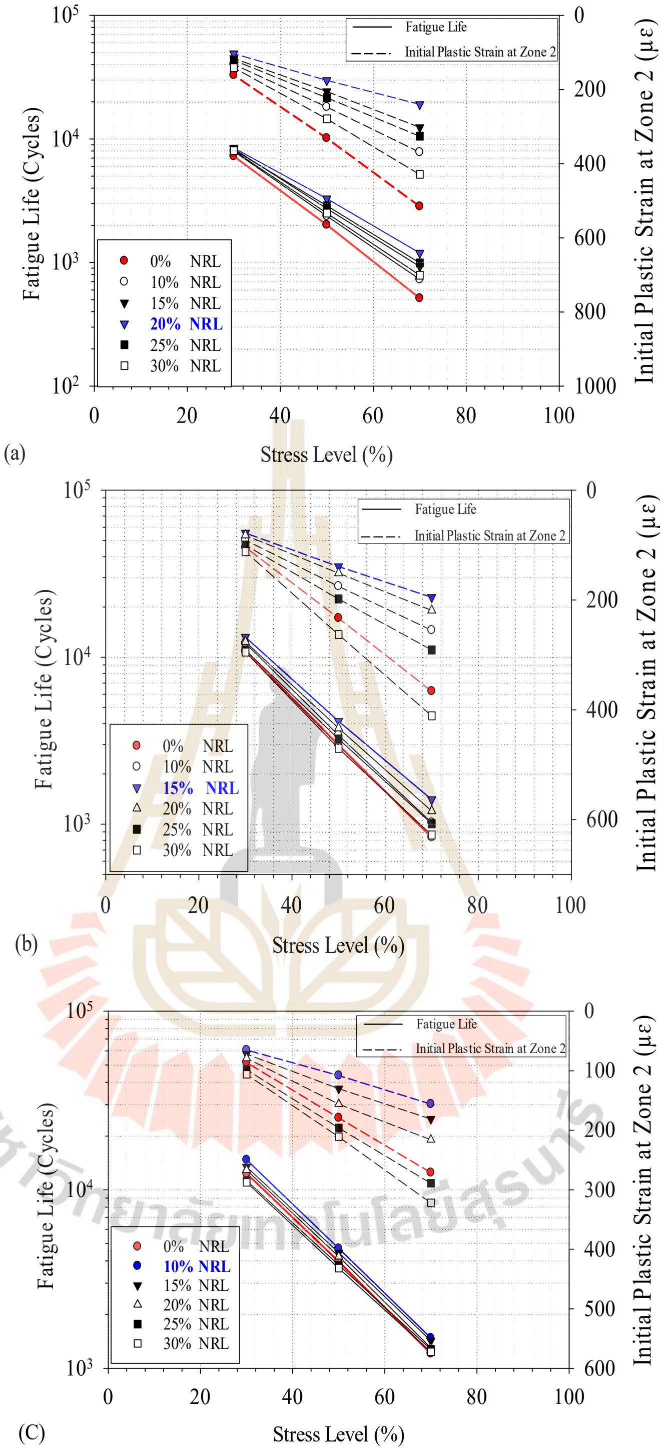

FIGURE 5.14 Relationship between initial strain and fatigue life at various NRL replacement ratio for (a) C = 3%, (b) C = 5%, and (c) C = 7% of soil A.

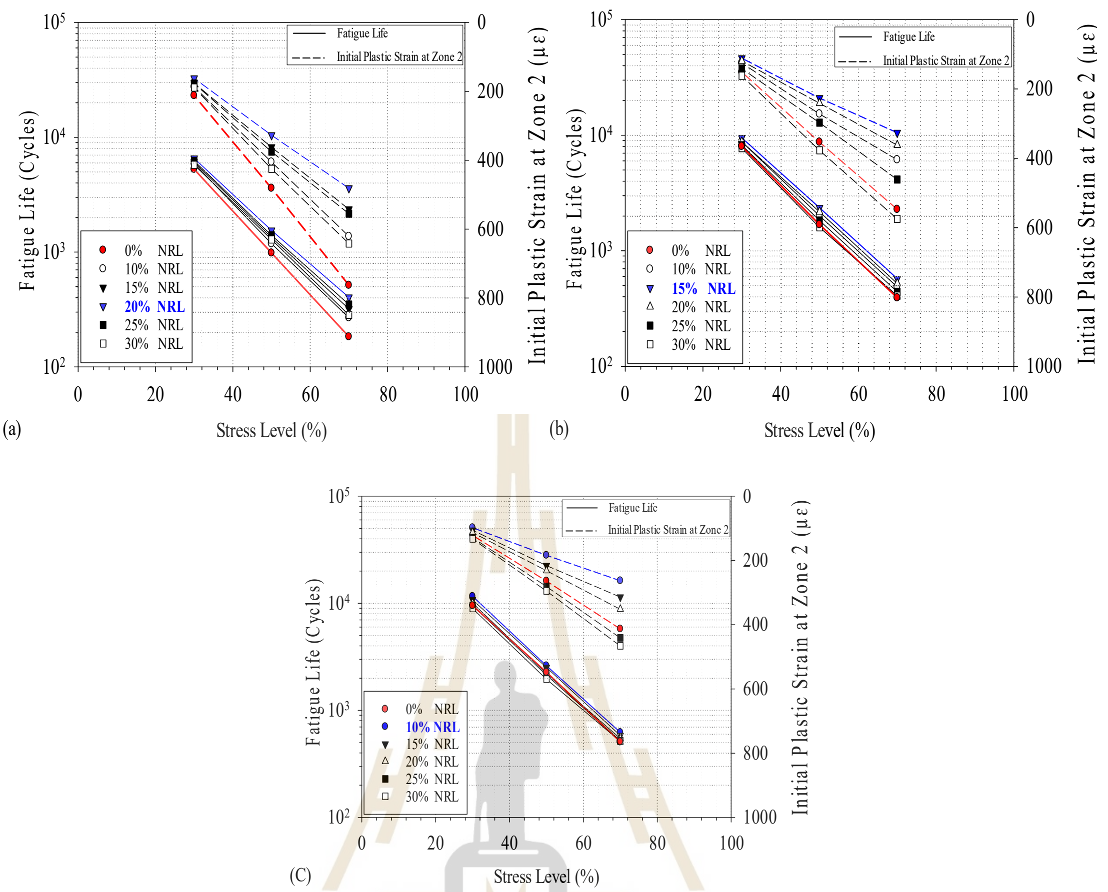

FIGURE 5.15 Relationship between initial strain and fatigue life at various NRL replacement ratio for (a) C = 3%, (b) C = 5%, and (c) C = 7% of soil C.

The NF of cement stabilized samples increases with the incremental cement content as a result of the higher cementitious products. For example, at stress level of 70%, the NF is 514, 833, and 1213 pulses for cement stabilized Soil A and is 183, 392, and 509 pulses for cement stabilized Soil C at C = 3%, 5%, and 7%, respectively. The relationship shows that the lower NF is associated with the higher initial plastic strain. The slope of the relationship between stress level versus ε_p shows the ability to resist the rutting depth due to the traffic load.

The gentler slopes of stress level versus NF and stress level versus ε_p at zone 2 indicate the higher capacity to withstand the developed plastic strain against fatigue damage under the imposed stress level. The slopes of the stress level versus NF and stress level versus initial strain at zone 2 relationships decrease as the cement content increases. The slope of stress level versus NF is -0.066, -0.061, and -0.058 for Soil A at C = 3%, 5%, and 7%, respectively. The slope of stress level and initial strain at zone 2 is 8.85, 6.55, and 4.63 for Soil A at C = 3%, 5%, and 7%, respectively. In other words, with reference to the same fatigue life, the samples with higher C have a lower plastic tensile strain.

The cement-NRL stabilized materials have the superior potential to withstand the accumulated plastic deformation to resist damage action under repetitive tensile stress. For both high and low stress levels, the cement-NRL stabilized samples at the optimum NRL ratio exhibits a higher NF and lower plastic strain than cement stabilized samples. The gentler slope of cement-NRL stabilized samples is found when compared with the cement stabilized samples at the same cement contents. The gentlest slope of the relationship is found at the optimum NRL replacement ratio, which is -0.057 and 3.43 (NRL = 20%), -0.056 and 2.93 (NRL = 15%) and -0.055 and 2.28 (NRL = 10%) for the stress level versus NF curves and stress level versus ε_p at zone 2 curves for Soil A at C = 3%, 5% and 7%, respectively.

Due to the higher plasticity and the lower ITS, Soil C possesses a higher plastic tensile strain at the same NF than Soil A; e.g. at NF = 3000 pulses, initial ε_p at zone 2 = 179.66 με and 250.22 με for Soil A and Soil C, respectively at C = 3% and NRL = 20%. Moreover, at the optimum NRL replacement ratio, the slope of both the relationships is higher for cement-NRL stabilized Soil C, which is -0.074

and 7.98, -0.073 and 5.38, and -0.072 and 4.13 for C = 3%, 5% and 7%, respectively. In other words, the higher soil plasticity has the higher risk opportunity of premature failure due to a higher accumulated plastic deformation.

At NRL replacement ratios beyond the optimum, the higher initial ε_p at zone 2 and lower NF at a particular stress level results in the higher slopes of both relationships, especially at 30% NRL replacement ratio. However, at 30% NRL replacement ratio, the cement-NRL stabilized samples still have higher NF and lower initial ε_p than the cement stabilized samples at high and low stress level for low cement content of C = 3%. The gentler slope of 3%C+30%NRL stabilized samples (Soil A) is found when compared with the cement stabilized samples, which is -0.061 and 7.20 for the stress level versus NF curves and stress level versus ε_p at zone 2 curves. For C = 5% and 7% at 30% NRL replacement ratio, the cement-NRL stabilized samples exhibit a lower NF and higher ε_p at zone 2 than the cement stabilized samples.

5.5 ENVIRONMENTAL ASSESSMENT

Regarding the greenhouse gas assessment, the carbon footprint has been considered a serious factor on the environmental impact assessing through the life cycle (Lazarevic and Martin, 2016 and McLellan et al. 2011). The carbon footprint emission of cement-NRL stabilized soil compared to that of the cement stabilized soil is illustrated in this section.

According to Turner and Collins (2013) and McLellan et al. (2011), the production of cement released greenhouse pollution with its high embodied energy. The carbon dioxide equivalent (CO_2-e) throughout its life cycle is 0.86 kg CO_2-e /kg.

Therefore, the input high amount of cement increases the risk factor on the emission of greenhouse gas.

The emission factor of concentrated latex of natural rubber throughout its life cycles is 0.143 kg CO_2-e /kg (Jawjit et al., 2010). With reference to the experimental results, NRL can reduce the input cement while improve the ITS and NF. It means that the replacement of cement by NRL can thereby effectively reduce the carbon footprints emission. The amount of chemical treatment in this studied NRL is little and it is the same raw materials with the concentrated latex of natural rubber. Hence, the emission factor of NRL is assumed to be 0.143 kg CO_2-e /kg.

In terms of the analytical comparison, the carbon footprints of both NRL and cement regarding materials transportation are not considered because both materials can easily be obtained in Thailand's market. Furthermore, the construction process for both cement stabilized soil and NRL-cement stabilized soil is practiced in the same way; NRL is used to replace water for NRL-cement stabilized soil. Consequently, pollution due to the construction process is not considered in the comparison.

Turner and Collins (2013) revealed that coarse-grained aggregate has been estimated the emission factor to be 0.0408 CO_2-e /kg. Although this presented value already includes quarrying and crushing, and the transportation procedures, it is still very low when compared to the values for cement and NRL. Hence, it is not considered in this comparative calculation.

Figure 5.16 demonstrates the amount of carbon footprint emission of cement-NRL stabilized Soil A compared to the cement stabilized Soil A at the same target ITS values. For this study, C = 3% at NRL replacement ratios of 10% to 30% were considered. The ITS results at 3% cement show that the cement-NRL stabilized Soil A has the ITS value = 0.585 MPa, 0.619 MPa, 0.648 MPa, 0.576 MPa and 0.535 MPa at NRL replacement ratios = 0%, 10%, 15%, 20%, 25% and 30%, respectively. While the cement stabilized soil has the same ITS values at C = 3.98%, 4.22%, 4.42%, 3.92% and 3.64%, respectively. The amount of cement of cement stabilized soil at each target ITS of cement-NRL stabilized soil was calculated based on the experimental results illustrated in **Figure 5.2**.

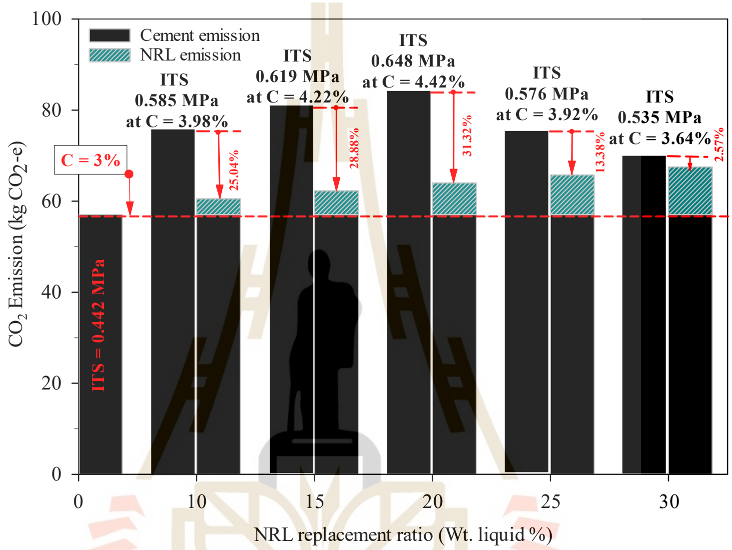

FIGURE 5.16 Relationship between Co$_2$-e Emission for cement stabilized Soil A with and without NRL at C = 3%.

It is evident from **Figure 5.16** that the CO_2-e emission for the cement-NRL stabilized Soil A is lower than that for cement stabilized Soil A at the same ITS values, which is 19.70%, 27.36%, 30.72%, 19.18%, and 6.24% for NRL replacement ratios of 10%, 15%, 20%, 25%, and 30%, respectively. The NRL is therefore considered as an environmentally friendly additive. The NRL can improve the ITS and NF of cement stabilized soil, which minimizes the maintenance time and cost. The extensive usage of NRL in pavement application will make the stable rubber market for Southeast Asia countries.

5.6 CONCLUSIONS

This research studied the influence of natural rubber latex (NRL) on the improvement of mechanical properties of cement stabilized soils for unpaved road applications. The indirect tensile strength and indirect tensile fatigue tests and evaluation of carbon footprints on cement-NRL stabilized samples were carried out at various cement contents, NRL replacement ratios, liquid contents and compaction energies. The conclusions can be drawn as follows:

1. The ITS and UCS are contributed from both cementitious products and NRL films, which improved cohesive matrix by means of reinforcements from NRL films formation. Though NRL films improves the soil cohesion, they retard the hydration. The UCS and ITS therefore increase with increasing the NRL replacement ratio up to the highest value at the optimum NRL replacement ratio, which is equal to 20%, 15%, and 10% at C = 3%, 5%, and 7%, respectively. The higher compaction energy led to the lower OLC and lower water to cement ratio at the same cement contents, hence the higher ITS.

2. The liquid content controlled the mechanical properties of cement-NRL stabilized samples. At 0.8 OLC, the ITS is the lowest because of insufficient liquid for cement hydration. At 1.2 OLC, the ITS values are higher than those at 0.8 OLC but lower than those at OLC. This higher liquid content (1.2 OLC) led to higher non-rubber component in NRL and water to cement ratio at the same cement content; hence lower cementitious products when compared to the ITS at OLC.

3. The normalized UCS and ITS of cement-NRL stabilized soils are controlled by the same influence factor. It is therefore logical to develop the relationship between ITS and UCS for cement-NRL stabilized soils as ITS = 0.208(UCS). This

relationship is useful for predicting ITS from UCS, which is simply obtained from conventional laboratory test.

4. The brittle behavior was observed for cement stabilized samples as indicated by the sudden failure at the transition between the second and third zones of the tensile fatigue test result. The high cement content caused the rapid cracking failure, particularly under high stress levels. The NF of cement-NRL stabilized samples increased with increasing the NRL replacement ratio and reached the maximum value at the optimum NRL replacement ratio. Although the cement-NRL stabilized samples exhibited higher total deformation, the plastic deformation was lower and the elastic deformation was higher when compared to results of the cement stabilized samples at the low and high stress levels.

5. The slopes of stress level versus NF and stress level versus ε_p at zone 2 indicated the capacity to withstand the developed plastic strain against fatigue damage under the imposed stress level. The slopes for the cement-NRL stabilized samples were found to be gentler when compared with those of the cement stabilized samples at the same cement contents. The gentlest slope of the relationship was found at the optimum NRL replacement ratio.

6. The soil plasticity controls the mechanical properties (UCS, ITS and NF) of cement-NRL stabilized soil. The higher soil plasticity caused the higher OLC, resulting in the higher water to cement ratio and the lower mechanical properties for the same input of cement. The higher plasticity also exhibits a higher total and plastic deformations and lower fatigue life at the same stress level for both samples with and without NRL.

7. The CO_2-e emission for the cement-NRL stabilized soil is lower than that for the cement stabilized soil at practically the same ITS, which is 19.70%, 27.36%, 30.72%, 19.18%, and 6.24% for NRL replacement ratios of 10%, 15%, 20%, 25%, and 30%, respectively. From the results of mechanical test and CO_2-e emission evaluation, the NRL is considered as an environmentally friendly additive for cement stabilization.

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CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and conclusion

This thesis consists of three major objectives. The first is to investigate the influence of NRL on the mechanical property of cement stabilized soil for pavement base/subbase applications. Compressive and flexural strengths were used as an indicator. The microstructural and chemical component of cement-NRL stabilized soil was observed through Scanning Electron Microscope (SEM) and Energy-dispersive X-ray spectroscopy (EDS) analysis. The influential factors studied in this study included water to NRL replacement ratios and cement content.

The second is to evaluate of the influence of NRL on durability against wetting and drying cycles of cement stabilized soil for pavement base/subbase applications. The effect of influence factors including soil type, NRL type, NRL replacement ratio, and cement content on the compressive strength prior to wetting and drying test (UCS0), cyclic wetting and drying compressive strength (UCS(w-d)) and weight loss was examined.

The third is to assess the tensile characteristic of cement-NRL stabilized soil. The effect of influence factors including type of soil, NRL replacement ratio, water content, different cement content, and different compaction energy on unconfined compressive strength (UCS), indirect tensile strength (ITS), and indirect tensile fatigue life (NF) were examined. The conclusions can be drawn as follows:

6.1.1 Chapter 3: Mechanical Strength Improvement of Cement-Stabilized Soil Using Natural Rubber Latex for Pavement Base Applications

This study investigated the influence of natural rubber latex (NRL) replacement on the mechanical strength improvement of cement-stabilized soil. Cement contents of 3%, 5%, and 7% by weight of dry soil and NRL replacement ratios of 10%, 15%, 20%, 25%, and 30% by weight of compacting water were used in this research study. NRL replacement was found to significantly enhance the mechanical strengths of cement-NRL stabilized soil. The optimum NRL replacement ratios providing the highest density, compression, and flexural strengths were found at 20%, 15%, and 10% for 3%, 5%, and 7% cement contents, respectively. Even though the NRL films within the soil-cement matrix improved the cohesion of the soil matrix, it was found to retard cementation bonding. As such, the excessive NRL replacement not only reduced the compatibility but also retarded the cement hydration and, hence, the strength reduction.

6.1.2 Chapter 4: Durability Improvement of Cement Stabilized Pavement Base Using Natural Rubber Latex

The effect of influence factors including soil type (low and high fines content), NRL type (low to high dry rubber content), NRL replacement ratio and cement content on the compressive strength prior to wetting and drying test (UCS_0), cyclic wetting, and drying compressive strength ($UCS_{(w-d)}$) and weight loss was examined in this study. The cement-NRL stabilized samples had higher UCS values than the cement stabilized samples, for all cement contents and NRL replacement ratios tested. The NRL films enhanced the cohesion (inter-particle forces) but retarded the hydration effects. The highest UCS value was found at an optimum NRL replacement ratio, which was 20%, 15%, and 10% for 3%, 5%, and 7% cement, respectively. The lowest weight loss and highest $UCS_{(w\text{-}d)}$ were also found at the optimum NRL replacement ratio. The $UCS_{(w\text{-}d)}$ of the cement-NRL stabilized samples was found to be higher than that of cement stabilized samples at all w-d cycles, even for the same UCS_0. For the same UCS = 4.4 MPa, the carbon footprint of 4.4% cement stabilized soil was reduced to 30.7% as compared to the 3% cement and 20% NRL stabilized soil.

6.1.3 Chapter 5: Improvement of Tensile Properties of Cement Stabilized Soil Using Natural Rubber Latex

The effect of influence factors including types of soil, NRL replacement ratio, water content, cement content and compaction energy on unconfined compressive strength (UCS), indirect tensile strength (ITS), and indirect tensile fatigue life (NF) were examined. The UCS, ITS, and NF increased with increasing the NRL replacement ratio up to the highest value at the optimum NRL replacement ratio, which is 20%, 15%, and 10% at C = 3%, 5%, and 7%, respectively. The maximum ITS were found at OLC and followed by 1.2OLC and 0.8OLC for the same input of cement and NRL. Although the cement-NRL stabilized samples exhibit higher total deformation under a particular fatigue tensile stress, the plastic deformation is remarkably lower when compared to the cement stabilized samples at the same cement contents. This indicated that the NRL replacement improved the capacity to withstand the developed plastic strain against fatigue.

6.2 Recommendations for future work.

6.2.1 The main objective of this study focused on the engineering properties improvement of cement-NRL stabilized soil. In addition, the recycled materials can be considered for further study.

6.2.2 The SDS surfactant was used to treat the NRL in this study. Further work can be developed using other related chemical substances to improve NRL performance.

6.2.3 Only DRC was considered to be the major factor affecting the properties of cement stabilized soil in this study. The other NRL components should be taken to account for further work.

6.2.4 The influence of wetting and drying cycles on the unconfined compressive strength was considered in this study. The tensile strength at various wetting and drying cycles of cement-NRL stabilized soil should be considered for further work.

6.2.5 The influence of clay minerals on the cement reaction affecting the NRL participation should be considered for further research.

6.2.6 The influence of the liquid content of NRL affecting the hydration process should be considered for further research.

APPENDIX A

PUBLICATIONS

List of Publications

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Mechanical Strength Improvement of Cement-Stabilized Soil Using Natural Rubber Latex for Pavement Base Applications

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Abstract: Thailand is an agricultural country, ranked as the top in the world for the production and export of natural rubber. This study investigated the influence of natural rubber latex (NRL) replacement on the mechanical strength improvement of cement-stabilized soil. Cement contents of 3%, 5%, and 7% by weight of dry soil and NRL replacement ratios of 10%, 15%, 20%, 25%, and 30% by weight of compacting water were used in this research study. The mechanical strengths were investigated via unconfined compressive strength (UCS) and flexural strength (FS) tests. The mechanical strengths improvements were examined through scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) analyses. NRL replacement was found to significantly enhance the mechanical strengths of cement-NRL stabilized soil. The optimum NRL replacement ratios providing the highest density, compression, and flexural strengths were found at 20%, 15%, and 10% for 3%, 5%, and 7% cement contents, respectively. At the optimum NRL replacement ratio, the UCS was improved up to 30%, 21%, and 18% for 3%, 5%, and 7% cement contents. While, FS was improved up to 78%, 40%, and 29% for 3%, 5%, and 7% cement contents. Even though the NRL films within the soil-cement matrix improved the cohesion of the soil matrix, it was found to retard cementation bonding. As such, the excessive NRL replacement not only reduced the compactability but also retarded the cement hydration and, hence, the strength reduction. The outcome of this research will promote the usage of NRL as a sustainable alternative to imported synthetic latexes for improving the mechanical strength of cement-stabilized soil for pavement bases. **DOI: 10.1061/(ASCE)MT.1943-5533.0003471.** *© 2020 American Society of Civil Engineers.*

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Introduction

A pavement structure is generally composed of base and subbase layers, which play an important role in the bearing capacity and serviceability of the road. This pavement structure requires high quality soil as a construction material. However, natural soils exhibit unfavorable physical and engineering properties, which are often not suitable for high volume road construction (Horpibulsuk et al. 2006; Sariosseiri and Muhunthan 2009; Baghini et al. 2014).

Soil improvement and ground improvement techniques have been adopted as an alternative method for improving the deficient quality materials to achieve the required criteria of a pavement construction material. The technique includes physical, mechanical, and chemical improvement methods. Chemical stabilization has been extensively researched and also widely employed in pavement applications by using a single additive or combined additives (Naeini et al. 2012; Marto et al. 2014). The stabilizers are practically divided into two main categories, namely, traditional and nontraditional additives (Onyejekwe and Ghataora 2015).

Traditional additives include lime, fly-ash, and cement. In general, the effectiveness and reliable performance of these substances have been extensively researched, usually related to their interaction behaviors. (Tingle et al. 2007). The utilization of Portland cement as a stabilizer is preferred to other additives in Southeast Asia, due to its cost effectiveness and the rapid enhancement of mechanical properties, including the bearing capacity, stiffness, and strength of the soil. Its hydration gradually generates cement matrix within the void space of soil to achieve the desirable strength

(Tingle and Santoni 2003; Horpibulsuk et al. 2005, 2010, 2012; Baghini et al. 2014). However, cement-stabilized soil, especially those with high fine contents, often exhibits brittle behavior under both flexural and compressive stress, which leads to macrocracks and microcracks in road structure and pavement (Jamsawang et al. 2015; Correia et al. 2015).

Nontraditional additives have been recently adopted to improve the engineering properties of marginal soils and have been found to improve shortcomings of cement-stabilized soil. Nontraditional additives can modify the microstructure of pavement materials to enhance the serviceability and durability of cement-stabilized soil. Nontraditional additives include enzyme, acid, salts, resins, natural resins, and polymers (Tingle et al. 2007; Estabragh et al. 2011; Rezaeimalek et al. 2017; Mirzababaei et al. 2018).

Synthetic polymer additives, such as polyvinyl alcohol and styrene–butadiene copolymer latex, have been widely used in the soil-cement stabilization (Thong et al. 2016; Baghini et al. 2014, 2016). The elastic property of cement-stabilized soil can be enhanced by the inclusion of polymers because they modify the porous structures by infiltration of the nano-composite. Moreover, the interparticle bonding strength between soil interparticles was enhanced by the polymerization of the nano-filler, resulting in the increase in both compressive and flexural strengths, durability, and the ductility of cement-stabilized soil (Azzam 2012, 2014; Latifi et al. 2014; Baghini et al. 2016; Mirzababaei et al. 2017; Rezaeimalek et al. 2017).

Thailand is an agricultural country and is ranked the top in the world for the production and export of natural rubber. In order to accelerate the country's economy, the Thailand government has encouraged the utilization of natural rubber, starting with propelling their usage from the industrial to the transportation sectors. According to the statistical data of the transport infrastructure status report 2018 (Thailand Office of Transport and Traffic Policy and Planning 2018), the growth of Thailand's road transportation system from 2018 to 2019 increased by more than 200,000 kilometers and is expected to further increase to support the economic growth.

Natural rubber latex (NRL), a suspended dispersion of *cis*-1,4-Polyisoprene, is typically polymerized from the *Hevea brasiliensis* tree. The suspended component, the raw-state liquid, consists of approximately 94% particles of rubber hydrocarbon and 6% of a nonrubber substance, which are composed of inorganic compound, sludge, acids, and protein. Based on the morphology and microstructural analysis, the particle size of the rubber latex is estimated to be in the range of 0.1–2.0 μm. The morphological shape of the NRL particle is a spherical molecule in the randomly packing state and is covered by the mixed layers of protein and phospholipids. The presence of proteins and phospholipids phases in the nonrubber components is an important factor for the coagulation and other undesired effects. However, these problems can be overcome by treating and surfactanting with the substances containing ammonia, zinc oxide, and sodium dodecyl sulfate to modify the rubber molecules to suitably apply in engineering or other works (Sakdapipanich 2007; Nawamawat et al. 2011; Afiq and Azura 2013; Norhanifah et al. 2015).

NRL has been researched and applied in concrete technology and mortar mixtures as an eco-friendly material (Nagaraj et al. 1988; Muhammad et al. 2011, 2012; Vo and Plank 2018; Pinwiset et al. 2018; Cheewapattananuwong et al. 2018; Pradhipa and Philip 2015). The nano-composite of NRL can form a latex film, which causes the transformation of the cement matrix to be the latex cement comatrix by the infiltration of polymer film within the porous (Muhammad and Ismail 2012; Diab et al. 2014). The utilization of NRL additives into concrete and mortar therefore has a significant effect on the strength and toughness development (Nagaraj et al. 1988). Moreover, the utilization of NRL additives has been found to enhance environmental resistance, acid resistance, sulphate resistance, and thermal degradation (Muhammad et al. 2011, 2012).

To the best of the authors' knowledge, there has been no research undertaken to date on the application of NRL to improve the engineering properties of cement-stabilized soil as a pavement base material, which is the focus of this research. NRL utilization in soil stabilization does not cause negative environmental impacts because NRL is a plant-based product, void of chemical hazards and petroleum components. A series of laboratory tests were carried out to evaluate the maximum dry density, optimum liquid (NRL and water), compressive strength, and flexural strength. Moreover, scanning electron microscopy (SEM) and energy dispersive X-Ray spectroscopy (EDS) were employed to confirm the evidence of the latex film formation and to investigate the chemical reaction within the soil-cement-NRL matrix, which controls the mechanical strength improvement. The outcome of this research will promote the usage of an NRL alternative to the imported synthetic latex in improving mechanical strength of cement-stabilized soil as a sustainable pavement base material.

Materials

Soil Sample

The soil samples were a coarse-grained soil, collected from a borrow pit in Nakhon-Ratchasima Province, Thailand. The grain size distribution is illustrated in Fig. 1, indicating 5.85% fine-grained particles and 94.15% coarse-grained particles in which 56.80% were gravel and 37.35% were sand. According to unified classification system, this soil was classified as GW-GC. Basic and engineering properties of soil are summarized in Table 1 and were compared with the Department of Highways standards for base and subbase materials [DH-S201/2544 (Thailand Department of Highways 1996a) and DH-S205/2532 (Thailand Department of Highways 1996c)]. It was found that the studied soil did not achieve the minimum requirements for both base and subbase materials. However, its properties met the requirement for a stabilized pavement base according to the DH-S204/2532 standard (Thailand Department of Highways 1996b).

Cement

Ordinary Portland cement was selected as a cementing agent. The chemical compositions are summarized in Table 2. The initial and

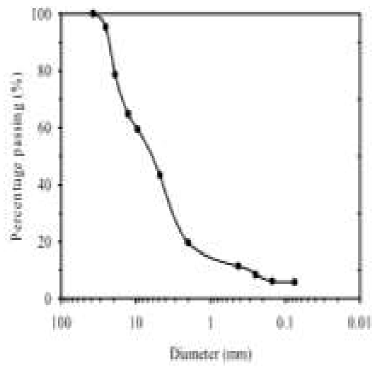

Fig. 1. Particle size distribution of soil.

Table 1. Basic and engineering properties of soil sample

Sample properties	Soil sample	Standard for base materials (DH-S201/2544)	Standard for subbase materials (DH-S205/2532)	Standard for stabilization of base materials (DH-S204/2532)
	Values			
Largest particle size (mm)	25	≤50	≤50	≤50
Los Angeles abrasion (%)	34	≤40	≤60	≤60
Liquid limit LL (%)	21	≤25	≤35	≤40
Plastic limit PL (%)	8	≤6	≤11	—
Plasticity index PI (%)	14	≤6	≤11	≤15
Specific gravity (G_s)	2.78	—	—	—
Maximum dry density (kN/m^3)	20.87	—	—	—
Optimum water content (%)	8.07	—	—	—
California bearing ratio (%)	18.16	≥80	≥25	—

Table 2. Chemical compositions of cement

Composition	Value (%)
Silicon dioxide	20.7
Sulphur oxide	4.8
Ferric oxide	3.1
Aluminum oxide	4.7
Calcium oxide	65.3
Magnesium oxide	2.8
Loss on ignition	0.9

Table 3. Properties of NRL

Properties	Values
Sludge content (%wt)	2.46
Coagulum content (%wt)	0.024
Specific gravity (G_s)	0.96
pH	8

final setting times were 101 minutes and 188 minutes, respectively. The compressive strengths at 7 days and 28 days were 24.7 MPa and 32.6 MPa, respectively.

Natural Rubber Latex

The natural rubber latex, obtained from the Rubber Authority of Thailand, was used in this research. It contained sodium dodecyl sulphate (SDS) as a surfactant to remove protein. Moreover, zinc 2-mercaptobenzothiazole (ZMBT), zinc oxide, calcium carbonate, and sulphur substance were included to improve workability and desired properties of NRL. The compositions are illustrated in Table 3. The total solid contents were 33.06% by total weight, which included the dry rubber content of 30.79% by total weight of NRL. The studied NRL is classified as the low category, having DRC lower than 31% (Muhammad et al. 2012).

Experimental Procedures

Preparation and Testing Condition

The soil samples were sieved to remove coarser aggregates larger than 19 mm and air-dried (Horpibulsuk et al. 2006). Portland cement was mixed with the soil samples at various contents of 3%, 5%, and 7% by weight of the dry soil. The Department of Highways, Thailand, specifies the minimum 7-day UCS as 1,724 and 2,413 kPa for low and high traffic volume roads, respectively (DH-S204/2532) (Thailand Department of Highways 1996b). This range of cement content used has been established in Thailand to meet the specified UCS.

The soil-cement mixture was then mixed with liquid (NRL and water) at different NRL replacement ratios of 10%, 15%, 20%, and 30% by weight of water. In order to obtain compaction characteristics according to the ASTM D1557 standard (ASTM 2012b), the cement and dried soil were thoroughly mixed together for 10 minutes and then mixed with liquid at various NRL replacement ratios for another 10 minutes prior to being compacted under modified Proctor energy. Because the NRL is in liquid form, the NRL replacement is determined in terms of optimum water content, which is practically applied in the real construction in Thailand. The maximum dry density (MDD) and optimum liquid content (OLC) values of each mix proportion were used to prepare the cement-stabilized samples for mechanical (compressive strength and flexural strength) tests and a microstructural analysis.

According to the AASHTO *Mechanistic-Empirical Pavement Design Guide* (AASHTO 2008), the ACI 230.1R-09 report [ACI 230, (ACI 2009)], and Thailand's Department of Highways standard (DH-S204/2532) (Thailand Department of Highways 1996b), the California bearing ratio (CBR) is not required for stabilized pavement design. It is appropriate for unbound pavement materials. As such, the CBR testing is not included in this research.

Unconfined Compressive Strength

The unconfined compressive strength (UCS) of unstabilized and stabilized samples was examined at different mixing ingredients to evaluate the influence of NRL on compressive strength. According to the ASTM D1633 standard (ASTM 2017), the samples were prepared by using a metallic mold with dimensions of 101.60 mm diameter and 116.8 mm height. At least three samples were prepared by a static compression machine at MDD and OLC to ensure the density's uniformity of the sample and the reliability of the test result. The samples were removed from the mold after 24 h and wrapped by plastic sheets. Subsequently, these compacted samples were stored in a humidity room at 25°C with a relative humidity of 95% for 7 days. The UCS tests on the 7-day samples were carried out at a compression rate of 1 mm/min by using a universal testing machine with an automatic data recorder.

Flexural Strength

The soil-cement road base structure often exhibits brittle behavior when subjected to the traffic load under flexural conditions.

The flexural strength (FS) tests on cement-stabilized samples were then carried out to investigate the role of NRL on the FS, which is an important factor for the pavement design. According to the ASTM D1635 standard (ASTM 2012a), the stabilized samples at various NRL ratios were statically compressed at MDD and OLC in a standard beam mold with dimensions of 76 mm height, 76 mm width, and 290 mm length. The samples were then demolded after 24 h, wrapped by plastic sheets, and cured for 7 days in a humidity room at 25°C with a relative humidity of 95%. The flexural tests were run using a universal testing machine at a deflection rate of 1 mm/min. The load and deflection were automatically recorded to determine the FS and failure state.

Scanning Electron Microscopy and Energy Dispersive X-Ray Spectroscopy

The morphology analysis was carried out by a scanning electron microscope, which is a high efficiency system to examine the microstructures of materials. The SEM samples were collected from the fraction of the UCS sample at the middle after being broken by strength testing. The small samples were immersed in liquid nitrogen at a freezing temperature of −195°C to stop cement hydration before gold coating. The 2500x magnification was selected to detect the change in morphology due to the NRL replacement randomly at least five points. The EDS analysis was employed to identify the chemical characterization of cement-stabilized samples by using an area mapping analysis to observe the impact of the NRL on mechanical strengths.

Results

Compaction Characteristic

The relationship between OLC and MDD of 3%, 5%, and 7% cement content at various NRL replacement ratios is summarized in Fig. 2. The MDD of cement-stabilized samples without NRL (water:NRL = 100:0) increases with increasing the cement content while the OLC slightly increases with increasing the cement content. This result is similar to the previous findings (Horpibulsuk et al. 2006; Sariosseiri and Muhunthan 2009; Baghini et al. 2016).

The OLC increases gradually with increasing the NRL replacement ratio for all cement contents tested, as presented in Fig. 2. The higher NRL replacement ratio (the lower water in total liquid) causes the higher OLC due to inadequate water for the compaction.

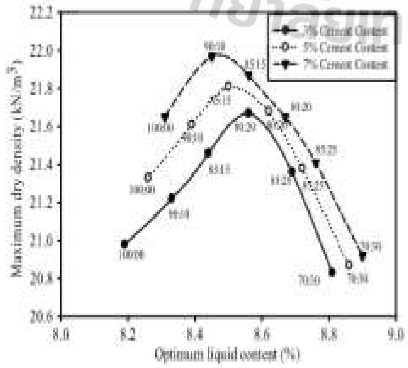

Fig. 2. Relationship between maximum dry density and optimum liquid content.

Initially, the higher NRL replacement ratio leads to the higher MDD in which the highest MDD values are found at the optimum NRL replacement ratios of 20%, 15%, and 10% for 3%, 5%, and 7% cement, respectively, because the compressibility of cement-stabilized soil is improved by the nano-composite of the latex. Infiltration of NRL in the soil-cement matrix causes the lubrication of interparticles, resulting in the increase in density with increasing the NRL replacement ratio. Beyond the optimum NRL replacement ratio, the MDD decreases as the NRL replacement ratio increases due to the excessive solid phase of NRL within the soil-cement matrix. In other words, the redundant NRL content transforms the soil-cement matrix to be weak structures; the excessive NRL replacement ratio is accompanied with the increased OLC, resulting in the excessive liquid content in the unit volume and the decrease in MDD. This result is similar to the previous research on cement and synthetic latex stabilized soil (Baghini et al. 2015).

The highest optimum NRL replacement ratio is found for the 3% cement, while for higher cement content (5% and 7%), the small amount of NRL replacement ratios are sufficient to fulfil the pore space. In the other words, the optimum NRL replacement ratio increases with decreasing the cement content. The NRL particles of 0.1–2.0 μm can be more coagulated at a higher cement content because the cement grains interacted with the nonrubber substance (Nagaraj et al. 1988; Muhammad et al. 2012). This coagulation interrupts the lubrication of interparticles and, hence, the reduction in compatibility of the cement-stabilized soil.

Unconfined Compressive Strength

The influence of the NRL replacement ratio at various cement contents on stress-strain behavior and UCS is presented in Figs. 3 and 4, respectively. The cement-stabilized soil clearly demonstrated brittle behavior with a small strain at failure, especially at a high cement content.

The incremental NRL replacement ratio evidently improved the ductile behavior and strain at the peak strength for all cement contents [Figs. 3(a–c)]. The increase of the strain at the peak strength improves the strain energy up to the peak strength, which is defined as the region under the stress-strain curve (Mirzababaei et al. 2017). The increase of UCS was observed with an increase in the NRL replacement ratio up to the optimum value. However, the deterioration of the strength improvement emerged by the further increase in the NRL replacement ratio beyond the optimum value. The samples can sustain more stress at a postpeak state due to the NRL replacement.

Fig. 4(a) shows the strength development with the NRL replacement ratio of cement-NRL stabilized soil at various cement contents. The dotted line in Fig. 4(a) indicates the minimum strength requirement for cement-stabilized base materials by the Department of Highways, Thailand (Thailand Department of Highways, 1996d). For the cement-stabilized samples without NRL, the UCS increases with increasing the cement content [Fig. 4(a)] because of the increased interparticle bonding strength within the soil matrix. The increased UCS is associated with a significant reduction in the strain at peak strength, showing the brittle behavior, as shown in Fig. 4(b) (Lorenzo and Bergado 2004; Horpibulsuk et al. 2010).

It is evident that the NRL replacement can enhance the UCS of cement-stabilized soil. The highest UCS value is found at optimum NRL replacement ratios of 20%, 15%, and 10% for 3%, 5%, and 7% cement, respectively. At the optimum NRL replacement ratios, the UCS values are improved up to 30%, 21%, and 18% higher than the UCS values when without NRL for 3%, 5%, and 7% cement, respectively. The percentage of improvement is higher for lower cement content.

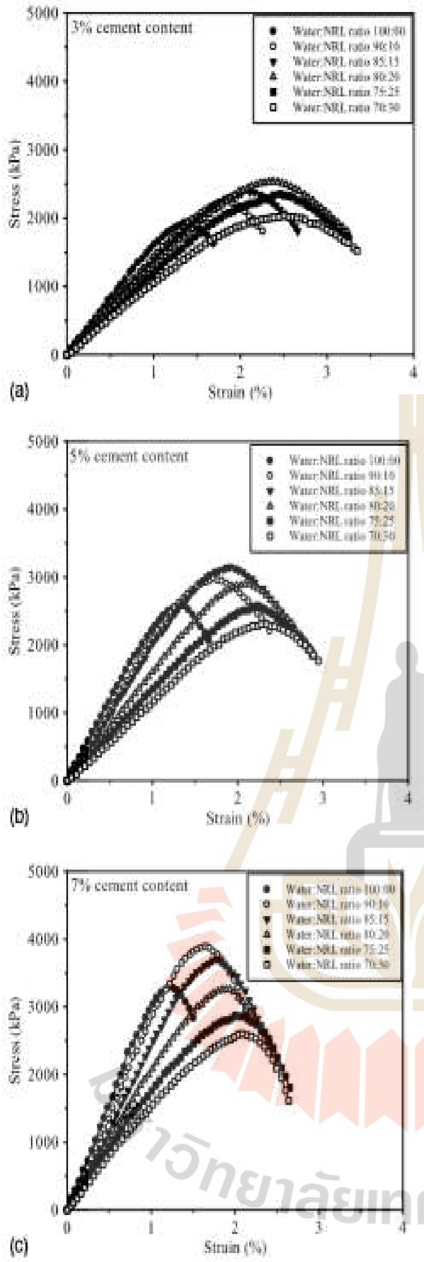

Fig. 3. Stress-strain behavior at various replacement ratios and cement contents of (a) 3% cement; (b) 5% cement; and (c) 7% cement.

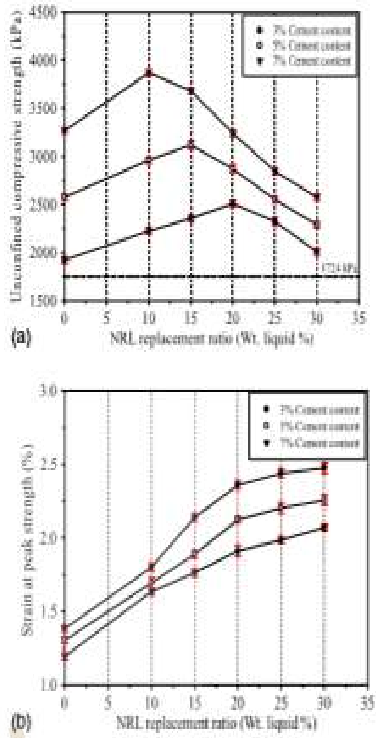

Fig. 4. Unconfined compressive test results for different cement contents and NRL replacement ratios: (a) unconfined compressive strength; and (b) strain at peak strength.

Flexural Strength

The FS tests were performed on the samples having the same mixing ingredients as the UCS tests to evaluate the role of NRL replacement on the modulus of rupture according to ASTM D1635. The test results are illustrated in Figs. 5–7.

The relationship between FS versus deformation for different cement contents and various NRL replacement ratios is summarized in Figs. 5(a–c). The FS development with increased cement content was clearly observed with the deflection-softening. The sudden failure after the peak FS is also observed for all cement contents, showing the brittle behavior.

The FS and deformation at failure are higher with a higher NRL replacement ratio, as shown in Fig. 5. The larger deformation at failure is associated with the region under the relationship between the flexural stress versus deformation, indicating the toughness improvement. The smaller stiffness, or rather the gentler slope of relationship between flexural stress versus deformation, is associated with the higher toughness. In other words, the ductility, toughness, and FS are improved by the NRL replacement for all cement contents. Moreover, the NRL replacement also improves the postpeak behavior. The NRL latex film, which is formed within soil-cement particles, can sustain a higher tensile stress after the break down of the cementation bonds and, hence, prevent the sudden failure after peak.

It is evident that the FS can be significantly improved by the increased latex film (Fig. 6). The optimum NRL replacement ratio providing the highest FS and UCS is the same for the same cement content (20%, 15%, and 10% for 3%, 5%, and 7% cement). Similar to UCS, the decrease of FS is found when the NRL replacement ratio exceeds the optimum value. However, the influence of NRL on the FS improvement is twice superior to that on the UCS improvement, i.e., the percentage of improvement at optimum NRC replacement ratios is found to be 78%, 40%, and 29% for 3%, 5%, and 7% cement, repetitively.

Because both UCS and FS are directly related to the NRL replacement ratio, it is logical to develop a relationship between

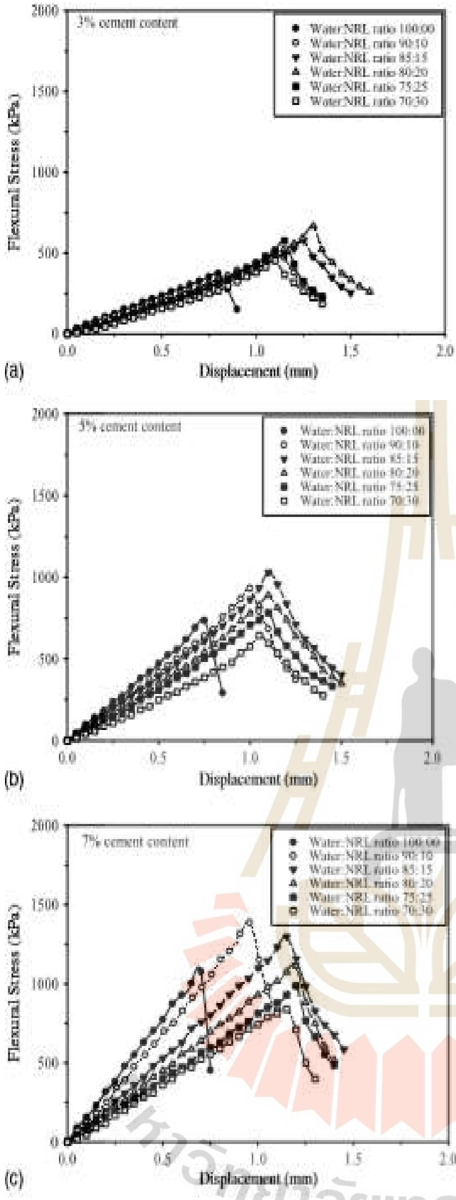

Fig. 5. Flexural behavior at various replacement ratios and cement contents of (a) 3% cement; (b) 5% cement; and (c) 7% cement.

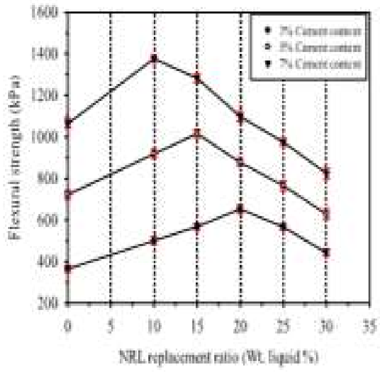

Fig. 6. Flexural strength at different cement contents and NRL replacement ratios.

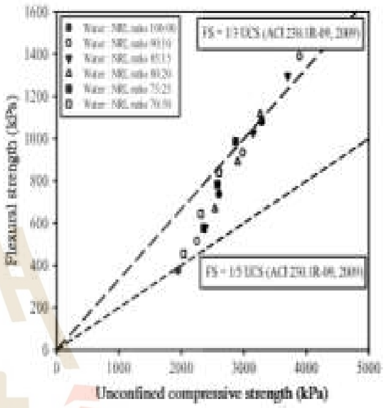

Fig. 7. Relationship between flexural strength and unconfined compressive strength.

FS versus UCS, as shown in Fig. 7, for different cement contents and NRL replacement ratios. The data points lie between two equations (FS = 1/5UCS and FS = 1/3UCS), which are suggested in ACI 230 (ACI 2009).

Microstructural Analysis

Scanning Electron Microscopic Images

Figs. 8(a–c) demonstrates the SEM image of cement-stabilized samples without NRL after 7 days of curing at 3%, 5%, and 7% cement, repetitively. The cementitious products are observed in the pore space. The cementitious products for the 3% cement sample are fewer when compared to 5% and 7% cement samples while the highest cementitious products are found at the 7% cement. These cementitious products not only fill up the pore space to reduce the void ratio but also enhance the interparticle bonding strength, which results in the significant strength development (Horpibulsuk et al. 2010).

The SEM images of the cement-NRL stabilized soil samples at optimum NRL replacement ratios and the maximum NRL replacement ratio of 30% for 3%, 5%, and 7% cement are presented in Figs. 9–10, respectively. Fig. 9 clearly shows the coexistence between soil-cement and NRL films for all cement contents. The latex film is infiltrated in the pore space and reduces the porosity. The microcracks are coated with interconnected films that cover soil particles under cement hydration products. The presence of more latex matrix is found for lower cement content due to the higher optimum NRL replacement ratio. Thicker and more continuous films are detected for the 3% cement sample [Fig. 9(a)]. While, the small latex films are plentifully distributed in the pore space for samples with higher cement contents [Figs. 9(b and c)]. Only thin and few latex films appear within the enormous cement

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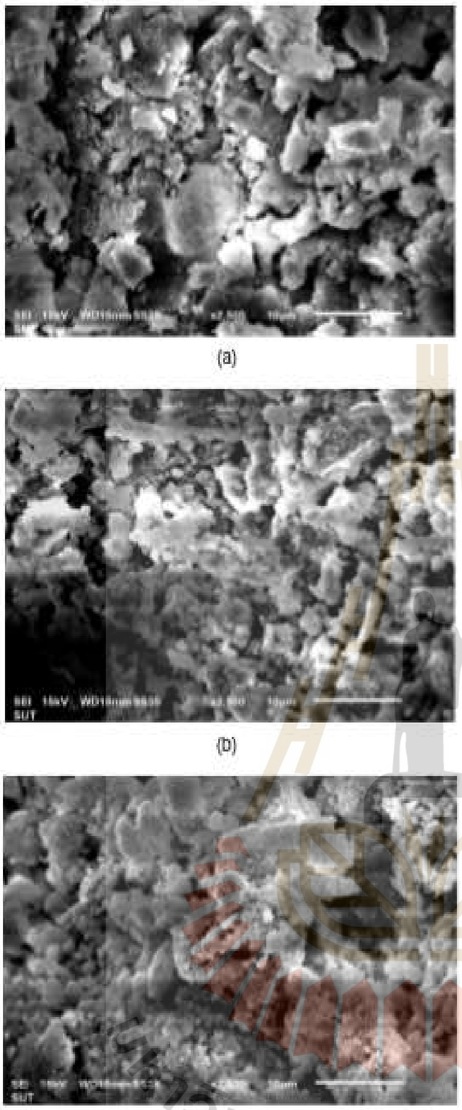
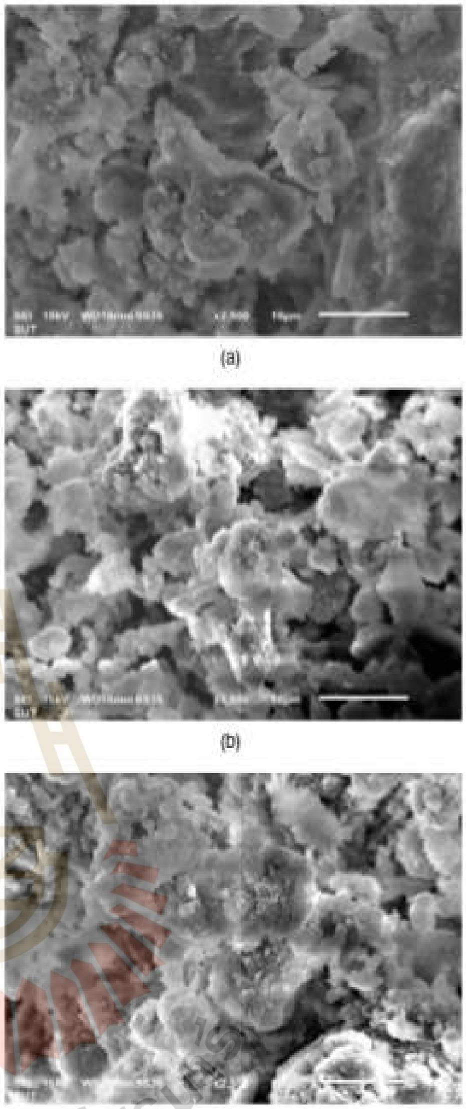


(a) (b) (c)

Fig. 8. SEM images of cement-stabilized soil at (a) 3% cement; (b) 5% cement; and (c) 7% cement.



(a) (b) (c)

Fig. 9. SEM images of samples at (a) 3% cement; (b) 5% cement; and (c) 7% cement and at optimum NRL replacement ratios.

structures and pore space, with very little continuous film network. Therefore, it is manifested that the samples with lower cement content allow more NRL replacement to complete a strong and dense packing state (highest strength and density). The formation of NRL films fills up the micropores in the cement-stabilized soil and possibly reduces the permeability. Therefore, the NRL films prevent water flow through the stabilized base/subbase layers and improve the resistance to swelling and collapse due to the climate change.

At the maximum 30% NRL replacement ratio (Fig. 10), the soil-cement matrix is covered with the excessive NRL film network, which forms a jelly-like surface. This causes the loose soil-cement structure with low density for all cement contents. Moreover, the coating of the latex network acts as the barrier-like reaction, which inhibits the water absorption of the hydration process (Yaowarat et al. 2019). Consequently, the hydration progress is retarded, resulting in the reduction in both UCS and FS.

Energy Dispersive X-Ray Spectroscopy (EDS)

The EDS technique by using an area mapping analysis at the corresponding area in the SEM testing was carried out on the 3% cement-stabilized samples with and without NRL, and the results

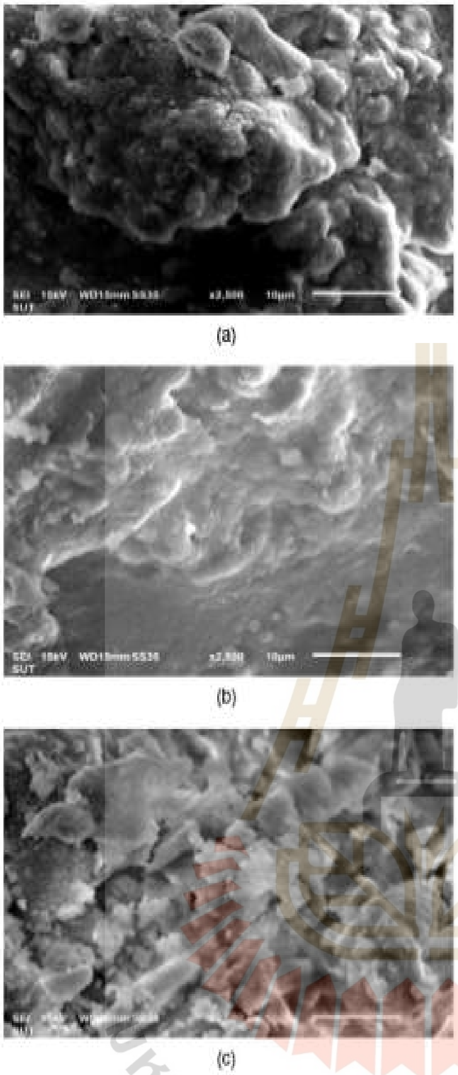


Fig. 10. SEM images of samples at (a) 3% cement; (b) 5% cement; and (c) 7% cement and at maximum NRL replacement ratios.

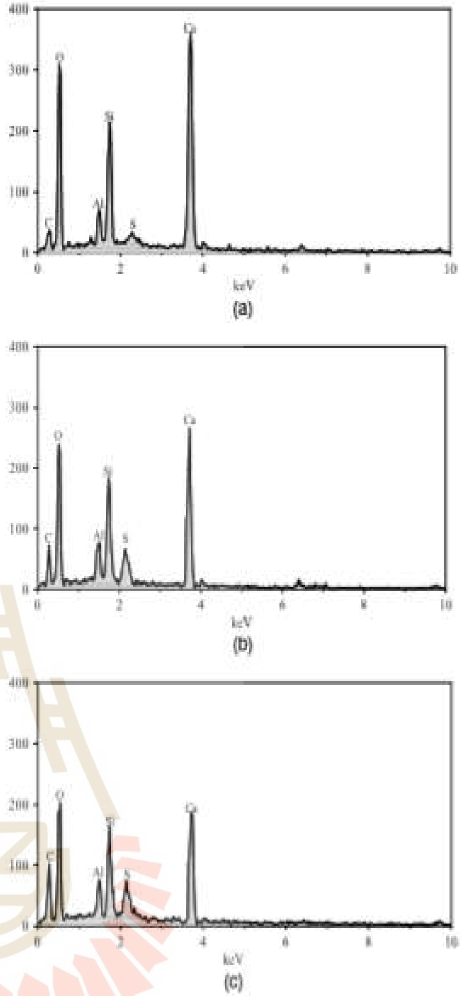


Fig. 11. EDS result of 3% cement samples for (a) without NRL; (b) optimum NRL; and (c) maximum NRL.

are shown in Figs. 11(a–c). This 3% cement samples were chosen because it contained more NRL participation than other samples.

The occurrence of C-S-H for the sample without NRL is detected by the prominent peaks of Ca and Si that are the major elements of hydration products, as indicated in Fig. 11(a). Several previous research works in biological and applied polymer innovation, by using the EDS analysis, have revealed that the major component of *cis*-1,4-Polyisoprene in the solid state of treated and untreated NRL consisted of carbon (C), more than 90% of atoms, and other components, such as hydrogen (H), zinc (Z_n), silicon (S_i), and less than 10% of atoms (Ho and Khew 1999; Herculano et al. 2011; Rathnayake et al. 2012). Therefore, the NRL matrix is generally contained of carbon as the major element.

At the optimum NRL replacement ratio [Fig. 11(b)], the hydration retardation due to the addition of the NRL causes the decrease of the C-S-H as seen by the lower peaks of Ca and Si elements and the increase of the C element from the NRL as compared with the 3% cement sample without the NRL [Fig. 11(a)]. This implies that although the growth of cementitious products is interrupted, the significant improvements of both compressive and flexural strengths are due to the adhesive bonding strength of latex within the soil-cement matrix. The excessive NRL replacement extremely prevents the growth of hydration products [Fig. 11(c)]. The retardation effect is detected by the appearance of the lowest apex of Ca and Si and the highest C element compared with the sample without the NRL [Fig. 11(a)].

From the SEM and EDS analysis, the highest compressive and flexural strengths are found to be at optimum NRL replacement ratios, which are 20%, 15%, and 10% for 3%, 5%, and 7% cement contents. The lowest UCS and FS values are observed at the maximum NRL replacement ratio of 30% for 5% and 7% of cement, while the lowest UCS and FS values for the 3% cement are found at a 0% NRL replacement ratio. For 3% cement, the slight decrease of UCS after the optimum NRL is caused by excessive NRL in the solid phase. At a low cement content, the hydration slightly affects the strength development, and therefore, the NRL replacement plays a significant role on the strength development by enhancing the latex network in the soil-cement matrix. As such, the cement-stabilized soil sample at the very high 30% NRL replacement ratio still has a higher UCS than the sample without the NRL. While at high cement contents (5% and 7%), the UCS contribution is strongly from the cementation bonding. Although the latex film can enhance the adhesion of the soil-cement matrix, at the same time, it retards the cement hydration. Hence, the optimum NRL replacement ratio reduces with increasing the cement content. Consequently, the lowest strength appeared at the maximum of the 30% NRL replacement ratio for both the 5% and 7% cement content.

It is evident from this research that the NRL significantly improves the mechanical strengths and microstructure of cement-stabilized base material. NRL as such will extend the service life of pavements. Many tropical countries, including those in Southeast Asia, suffer from annual drought and flood events, which may cause the degeneration of the stabilized pavement base and subbase. The examination of long-term and strength behavior via the durability tests against wetting-drying cycles and sulfate attacks, and of the field performance of cement-NRL stabilized soil, is recommended for further research to ascertain the applicability of cement-NRL stabilization in practice.

Conclusions

This research studied the influence of natural rubber latex on the improvement of mechanical strengths of cement-stabilized soil for pavement applications. The microstructural analysis was also carried out on the cement-NRL stabilized soil to examine the influence of NRL. The conclusions can be drawn as follows:

- The compactibility, compressive strength, and flexural strength of cement-stabilized soil could be improved by an NRL replacement. The NRL replacement lubricated the soil particles and led to the dense structure after compaction. The cementation and latex film network enhanced the interparticle bonding strength, and consequently, both the compressive strength and flexural strength were increased.
- The highest dry density, compressive strength, and flexural strength for each cement content were observed at the optimum NRL replacement ratio. The optimum NRL replacement ratio was lower for the higher cement content, which were 20%, 15%, and 10% for 3%, 5%, and 7% cement content, repetitively.
- The microstructural analysis confirmed the influence of the latex matrix on the mechanical strength improvement of cement-NRL stabilized soil. At the optimum NRL replacement ratio, the thick and continuous films of NRL were clearly observed for the low cement content of 3%, while the thinner latex films within the soil-cement matrix were detected at higher cement contents of 5% and 7%. This indicates that the samples with a lower cement content can absorb more NRL at the densest packing stage.
- At the optimum NRL replacement ratio, the UCS was improved up to 30%, 21%, and 18% for 3%, 5%, and 7% cement contents. While, the FS was improved up to 78%, 40%, and 29% for 3%, 5%, and 7% cement contents. The FS to UCS ratios laid between 1/5 and 1/3, which was in agreement with the ACI 203 (ACI 2009).
- The NRL replacement enhanced the interparticle cohesion, but at the same time, it retarded the cementation bonding, as seen by the EDS analysis result. As such, the mechanical strengths of the cement-NRL stabilized soil decreased when the NRL replacement ratios exceeded the optimum value. The excessive latex content took the place of the soil-cement matrix in the solid phase and caused the loose and weak structures.

Data Availability Statement

Some or all data, models, or code that support the finding of this study are available from the corresponding author upon reasonable request. All data shown in the figures and tables can be provided on request.

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