การปรับปรุงประสิทธิภาพของดินซีเมนต์บดอัดโดยการแทนที่มวลรวมบางส่วนด้วยวัสดุรีไซเคิล และน้ำยางธรรมชาติเพื่อประยุกต์ใช้งานถนน

ธี ง็อก ควิน ตรัน

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต
สาขาวิชาวิศวกรรมโยธา ขนส่ง และทรัพยากรธรณี
มหาวิทยาลัยเทคโนโลยีสุรนารี
ปีการศึกษา 2565

IMPROVED PERFORMANCE OF CEMENT-STABILIZED LATERITIC SOIL USING RECYCLED MATERIALS REPLACEMENT AND NATURAL RUBBER LATEX FOR PAVEMENT APPLICATIONS

THI NGOC QUYNH TRAN

A Thesis Submitted in Partial Fulfillment of the Requirements for the

Degree of Doctor of Philosophy in Civil, Transportation

and Geo-resources Engineering

Suranaree University of Technology

Academic 2022

IMPROVED PERFORMANCE OF CEMENT-STABILIZED LATERITIC SOIL USING RECYCLED MATERIALS REPLACEMENT AND NATURAL RUBBER LATEX FOR PAVEMENT APPLICATIONS

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

Thesis Examining Committee

....

(Prof. Dr. Panich Voottipruex)

Chairperson

....

(Asst. Prof. Dr. Menglim Hoy)

Member (Thesis advisor)

....

(Prof. Dr. Suksun Horpibulsuk)

Member (Thesis Co-Advisor)

....

(Prof. Dr. Avirut Chinkulkijniwat)

Member

....

(Assoc. Prof. Dr. Cherdsak Suksiripattanapong)

Member

....

(Dr. Apichat Suddeepong)

Member

....

(Assoc. Prof. Dr. Chatchai Jothityangkoon)

Vice Rector for Academic Affairs and Quality Assurance

....

(Assoc. Prof. Dr. Pornsiri Jongkol)

Dean of Institute of Engineering

ธี ง็อก ควิน ตรัน: การปรับปรุงประสิทธิภาพของดินซีเมนต์บดอัดโดยการแทนที่มวลรวมบางส่วนด้วยวัสดุรีไซเคิลและน้ำยางธรรมชาติเพื่อประยุกต์ใช้งานถนน (IMPROVED PERFORMANCE OF CEMENT-STABILIZED LATERITIC SOIL USING RECYCLED MATERIALS REPLACEMENT AND NATURAL RUBBER LATEX FOR PAVEMENT APPLICATIONS) อาจารย์ที่ปรึกษา: ผู้ช่วยศาสตราจารย์ ดร. MENGLIM HOY, Ph.D., 184 PP.

คำสำคัญ: วัสดุรีไซเคิล/การปรับปรุงคุณภาพด้วยซีเมนต์/น้ำยางธรรมชาติ/ถนนชั้นพื้นทาง

งานวิจัยนี้มีวัตถุประสงค์เพื่อศึกษาศักยภาพของการใช้วัสดุรีไซเคิลและน้ำยางธรรมชาติ (NRL) ในการปรับปรุงสมรรถนะของดินลูกรังที่ปรับปรุงด้วยซีเมนต์สำหรับประยุกต์ใช้ในงานถนน งานวิจัยนี้ใช้ตะกรันเหล็ก (SS) และมวลรวมคอนกรีตรีไซเคิล (RCA) แทนที่ในดินลูกรังร้อยละ 50 และ 70 ใช้ปริมาณปูนซีเมนต์ร้อยละ 5 และใช้อัตราส่วนยางแห้งต่อปริมาณปูนซีเมนต์ (r/c) ร้อยละ 0 3 5 10 และ 15 แฟคเตอร์อิทธิพล เช่น อัตราส่วนตะกรันเหล็กต่อดินลูกรัง (SS:LS) อัตราส่วนมวลรวมคอนกรีตรีไซเคิลต่อดินลูกรัง (RCA:LS) และอัตราส่วนยางแห้งต่อปริมาณปูนซีเมนต์ (r/c) ถูกตรวจสอบผ่านการทดสอบทางธรณีเทคนิคในห้องปฏิบัติการ 3 ส่วน ได้แก่ ส่วนที่ 1 การทดสอบกำลังอัดแกนเดียว (UCS) กำลังดึงทางอ้อม (ITS) และการวิเคราะห์โครงสร้างจุลภาคด้วยกล้องจุลทรรศน์อิเล็กตรอนแบบส่องกราด (SEM) และการวิเคราะห์องค์ประกอบทางเคมี (XRD) ส่วนที่ 2 การทดสอบโมดูลัสคืนตัวเนื่องจากแรงดึงทางอ้อม (IT M_r) และการล้าเนื่องจากแรงดึงทางอ้อม (IT F_n) เพื่อประเมินโมดูลัสคืนตัวและอายุการล้าของดินลูกรังผสมวัสดุรีไซเคิลปรับปรุงด้วยซีเมนต์และน้ำยางธรรมชาติภายใต้แรงกระทำพลวัต และส่วนที่ 3 การทดสอบความทนทานต่อวงจรเปียกสลับแห้งของดินลูกรังผสมวัสดุรีไซเคิลปรับปรุงด้วยซีเมนต์และน้ำยางธรรมชาติ โดยการพิจารณาจากค่า UCS การสูญเสียน้ำหนัก การดูดซึมน้ำ และโครงสร้างทางจุลภาคที่เปลี่ยนแปลงไปภายใต้วงจรเปียกสลับแห้ง

ผลการศึกษาด้านกำลังของดินลูกรังผสมวัสดุรีไซเคิลปรับปรุงด้วยซีเมนต์และน้ำยางธรรมชาติแสดงให้เห็นถึงความสามารถต่อการใช้เป็นวัสดุพื้นทาง โดยที่กำลังของวัสดุผ่านมาตรฐานด้านกำลังที่กำหนดโดยกรมทางหลวงของประเทศไทย ปฏิกิริยาร่วมระหว่างผลิตภัณฑ์ไฮเดรชั่นของซีเมนต์และโครงข่ายฟิล์มจากน้ำยางธรรมชาติที่ก่อตัวขึ้นที่อัตราส่วน r/c เหมาะสม สามารถลดช่องว่างภายในโครงสร้างของดินซีเมนต์และเพิ่มแรงยึดเหนี่ยวระหว่างอนุภาค ส่งผลให้เกิดการพัฒนากำลังของส่วนผสมที่ปรับปรุงด้วยปูนซีเมนต์และน้ำยางธรรมชาติ อัตราส่วน r/c ที่เหมาะสมสำหรับการปรับปรุงดินลูกรังผสมตะกรันเหล็กปรับปรุงด้วยซีเมนต์และยางธรรมชาติ และดินลูกรังผสมมวลรวมคอนกรีตรีไซเคิลปรับปรุงด้วยซีเมนต์และยางธรรมชาติ มีค่าเท่ากับร้อยละ 3 และ 5 ตามลำดับ ซึ่งจะให้ค่า UCS ITS IT M_r และ IT F_n สูงที่สุดและมีค่าสูงกว่าดินลูกรังผสมตะกรันเหล็กปรับปรุงด้วย

ซีเมนต์และดินลูกรังผสมมวลรวมคอนกรีตรีไซเคิลปรับปรุงด้วยซีเมนต์ อย่างไรก็ตาม เมื่ออัตราส่วน r/c สูงกว่าค่าเหมาะสม น้ำยางธรรมชาติที่มากเกินไปจะทำให้เกิดชั้นฟิล์มหนาและขัดขวางกระบวนการเกิดผลิตภัณฑ์ไฮเดรชั่นของซีเมนต์ทำให้การพัฒนากำลังลดลง ดินลูกรังผสมตะกรันเหล็กปรับปรุงด้วยซีเมนต์และน้ำยางธรรมชาติมีสมบัติเชิงกลและสมบัติการล้าเหนือกว่าดินลูกรังผสมมวลรวมคอนกรีตรีไซเคิลปรับปรุงด้วยซีเมนต์และยางธรรมชาติ นอกจากนี้ ดินลูกรังผสมวัสดุรีไซเคิลปรับปรุงด้วยปูนซีเมนต์และน้ำยางธรรมชาติ ที่ใช้อัตราส่วนการแทนที่ดินลูกรังด้วยวัสดุรีไซเคิลร้อยละ 70 มีสมบัติเชิงกลและสมบัติการล้าสูงกว่าตัวอย่างที่มีการแทนที่ดินลูกรังด้วยวัสดุรีไซเคิลร้อยละ 50 สมบัติเชิงกลและสมบัติการล้าของวัสดุผสมที่ปรับปรุงด้วยปูนซีเมนต์และน้ำยางธรรมชาติขึ้นอยู่กับอัตราส่วน r/c ดังนั้น ความสัมพันธ์ระหว่าง UCS ITS IT M_r และ IT F_n และอัตราส่วน r/c ค่าต่างๆ ของดินลูกรังผสมตะกรันเหล็กปรับปรุงด้วยซีเมนต์และน้ำยางธรรมชาติ และดินลูกรังผสมมวลรวมคอนกรีตรีไซเคิลปรับปรุงด้วยซีเมนต์และยางธรรมชาติ จึงถูกสร้างขึ้นด้วยความแม่นยำสูง ผลทดสอบความทนทาน แสดงให้เห็นว่า UCS_{w-d} ของวัสดุผสมที่ปรับปรุงด้วยปูนซีเมนต์และน้ำยางธรรมชาติมีค่าเพิ่มขึ้นตามรอบการทดสอบเปียกสลับแห้งที่เพิ่มขึ้นจนถึงรอบการทดสอบที่สามและมีค่าลดลงหลังจากผ่านรอบการทดสอบที่สาม ภาพถ่าย SEM ปรากฏแผ่นฟิล์มยางธรรมชาติภายในช่องว่างและรอยแตกขนาดเล็กของโครงสร้างดินลูกรังผสมตะกรันเหล็กปรับปรุงด้วยซีเมนต์และน้ำยางธรรมชาติและโครงสร้างดินลูกรังผสมมวลรวมคอนกรีตรีไซเคิลปรับปรุงด้วยซีเมนต์และยางธรรมชาติ ซึ่งส่งผลให้ UCS_{w-d} มีค่าสูงกว่า การสูญเสียน้ำหนักและการดูดซึมน้ำมีค่าต่ำกว่า เมื่อเทียบกับตัวอย่างที่ไม่ผสมน้ำยางธรรมชาติ

งานวิจัยนี้จะให้ข้อมูลเชิงลึกใหม่เกี่ยวกับการปรับปรุงสมบัติเชิงกลของดินลูกรังผสมซีเมนต์ด้วยการแทนที่ด้วยวัสดุรีไซเคิลและการผสมน้ำยางธรรมชาติสำหรับประยุกต์ใช้ในงานถนน การประยุกต์ใช้วัสดุรีไซเคิลไม่เพียงปรับปรุงสมบัติที่บกพร่องของดินลูกรังให้เป็นไปตามข้อกำหนดสำหรับถนนที่มีปริมาณจราจรสูงของหน่วยงานระดับนานาชาติและหน่วยงานในท้องถิ่น แต่ยังมีส่วนช่วยในการแก้ปัญหาสิ่งแวดล้อมที่เกิดจากการเพิ่มขึ้นของวัสดุเหลือทิ้ง ด้วยสมบัติยืดหยุ่นและแรงดึงที่คล้ายคลึงกันกับวัสดุผสมเพิ่มจำพวกโพลิเมอร์สังเคราะห์ น้ำยาพาราธรรมชาติจึงจัดเป็นวัสดุผสมเพิ่ม "สีเขียว" เพื่อการปรับปรุงโครงสร้างจุลภาคและสมบัติทางกลของวัสดุที่ปรับปรุงด้วยซีเมนต์ทดแทนการใช้โพลิเมอร์สังเคราะห์ ข้อด้อยของวัสดุที่ปรับปรุงด้วยซีเมนต์ เช่น พฤติกรรมแบบเปราะและความทนทานต่ำ ยังสามารถปรับปรุงด้วยน้ำยางพาราได้อีกด้วย

สาขาวิชา วิศวกรรมโยธา ลายมือชื่อนักศึกษา..........................

ปีการศึกษา 2565 ลายมือชื่ออาจารย์ที่ปรึกษา..........................

ลายมือชื่ออาจารย์ที่ปรึกษาร่วม..........................

THI NGOC QUYNH TRAN: IMPROVED PERFORMANCE OF CEMENT-STABILIZED LATERITIC SOIL USING RECYCLED MATERIALS REPLACEMENT AND NATURAL RUBBER LATEX FOR PAVEMENT APPLICATIONS.
THESIS ADVISOR: ASST. PROF. DR. MENGLIM HOY, Ph. D., 184 PP.

Keywords: Recycled Materials/Cement Stabilization/Natural Rubber Latex/Pavement Base Applications

This research aims to study the potential of using recycled materials and natural rubber latex (NRL) in improving the performance of cement-stabilized lateritic soil for pavement applications. The steel slag (SS) and recycled concrete aggregate (RCA) replacement ratios of 50% and 70% were studied. The cement content of 5% by weight and dry rubber to cement (r/c) ratios of 0%, 3%, 5%, 10%, and 15% were examined. Geotechnical laboratory experimental programs were investigated under several influent factors such as steel slag-to-lateritic soil (SS:LS) ratios, recycled concrete aggregate-to-Lateritic soil (RCA:LS) ratios, dry rubber-to-cement (r/c) ratios in order to clarify three main objectives of the research. Firstly, unconfined compressive strength (UCS) and indirect tensile strength (ITS) tests, and microstructure analysis including scanning electron microscope (SEM) and X-ray diffraction (XRD) were performed. Secondly, indirect tensile resilient modulus (IT M_r) and indirect tensile fatigue (IT F_n) tests were conducted in order to assess the resilient modulus and fatigue life of cement-NRL stabilized recycled materials and lateritic soil blends under cyclic loading conditions. Finally, the durability against wetting-drying (w-d) cycles test of cement-NRL stabilized recycled materials and lateritic soil blends was performed. The unconfined compressive strength (UCS_{w-d}), weight loss, water absorption, and microstructural change were considered as the results of the w-d cycles test.

The strength results showed that the cement-NRL stabilized recycled materials and lateritic soil blends can be used as pavement base course materials as their strength meets the minimum strength requirement specified by Department of Highway, Thailand. The coexistence of cement hydration products and NRL films

formed by optimum NRL content (optimum r/c ratio) can reduce the pore space and enhance the interparticle bond strength, resulting in the strength development of cement-NRL stabilized blends. The optimum r/c ratio was found to be 3% and 5% for cement-NRL stabilized SS:LS and RCA:LS blends, respectively producing the highest values of UCS, ITS, IT M_r, and IT F_n, which were higher than those of cement stabilized SS:LS and RCA:LS blends. However, beyond the optimum r/c ratio, the excessive amount of NRL generated thick NRL films and retarded the cement hydration process, resulting in low-strength development. The cement-NRL stabilized SS:LS blends exhibited higher mechanical strength properties and fatigue properties than the cement-NRL stabilized RCA:LS blends. In addition, for both types of recycled materials, the cement-NRL stabilized SS/RCA:LS blends with 70% recycled material replacement ratio exhibited superior mechanical strength and fatigue properties than the samples with 50% recycled material replacement ratio. It was also found that the mechanical strengths and fatigue properties of cement-NRL stabilized studied blends reliant on the r/c ratio. Hence, the relationship between UCS, ITS, IT Mr, and IT Fn of cement-NRL stabilized SS:LS and RCA:LS samples at various r/c ratios was established with high accuracy. The durability test result showed that the UCS_{w-d} of cement-NRL stabilized blends increased with the increase of the number of w-d cycles, up to the third cycle and then decreased beyond 3 cycles. The SEM images also indicated that the presence of NRL films infiltrates pores and cracks of cement-stabilized structure, resulting in the higher UCS_{w-d} and lower weight loss and water absorption of cement-NRL stabilized SS:LS and RCA:LS blends compared to the cement stabilized SS:LS and RCA:LS blends.

This research will provide new insights into improved mechanical of cement-stabilized lateritic soil using recycled materials replacement and natural rubber latex for pavement applications. Recycled materials applications are not only improving the unfavorable properties of lateritic soil to comply with the specifications for high volume roads designated by international or local road authorities but also contribute to solving the environmental burden due to the increasing waste materials. With similar elastic and tensile properties to synthetic polymer additives, NRL is recognized as a "green" additive to improve the microstructure and mechanical properties of cement-stabilized materials alternate to Synthetic polymer additives. The shortcoming of cement-stabilized materials such as brittle behavior as well as durability can also be enhanced by using natural rubber latex.

School of Civil Engineering

Academic year 2022

Student's Signature............................

Advisor's Signature............................

Co-Advisor's Signature............................

ACKNOWLEDGMENT

First and Foremost, I wish to extend my deepest appreciation to my advisor Asst. Prof. Dr. Menglim Hoy for his supervision, encouragement, and support, all of which have given me great benefits for my expert knowledge and skill improvement. He always not only gave me his time and support every time even he was in his hectic schedule but also encouraged me with his patience and endless kindness especially when I met trouble in research work throughout my Ph.D. study at Suranaree University of Technology. I am also extremely grateful to my Co-Advisor Prof. Dr. Suksun Horpibulsuk for giving me the opportunity to study at the Suranaree University of Technology, imparting a wealth of knowledge, and providing unwavering support during my Ph.D. program. It is such a best luck that I can work with Asst. Prof. Dr. Menglim Hoy and Prof. Dr. Suksun Horpibulsuk, and have them as my supervisors. I am able to be more knowledgeable, and I believe this is my most unforgettable journey along with their supervision. Without their guidance and persistent assistance, this thesis would not have been possible.

I would like to sincerely thank Asst. Prof. Dr. Pornpot Tangseng, Prof. Dr. Avirut Chinkulkijniwat, and Dr. Nattaporn Charoentham, School of Civil Engineering, Suranaree University of Technology, for their influential lectures and for teaching students with kindness.

Besides, I would like to express my gratitude to my thesis committee: Prof. Dr. Panich Voottipruex, Prof. Dr. Avirut Chinkulkijniwat, Assoc. Prof. Dr. Cherdsak Suksiripattanapong, and Dr. Apichat Suddeepong for their encouragement, insightful comments, and constructive suggestions.

In addition, a profound gratitude is expressed to Prof. Dr. Arul Arulrajah of Department of Civil and Construction Engineering at Swinburne University of Technology, Australia for his reviews, and suggestions of my research, which are very helpful for developing excellent manuscripts published in the leading international journals.

I wish to acknowledge the financial support from Suranaree University of Technology under SUT Scholarships for Graduate International Students (Vithedbundith) during my Ph.D. study. This work was financially supported by the National Science and Technology Development Agency under the Chair Professor Program Grant No. P-19-52303, Suranaree University of Technology and Thailand Science Research and Innovation (TSRI). This research project was also funded by National Research Council of Thailand (NRCT) under Young Researcher Genius Program Grant No. N42A650210. Financial support, facilities, and equipment from the Suranaree University of Technology are very much appreciated.

I would like to acknowledge the valuable support from Dr. Apichat Suddepong, Dr. Teerasak Yaowarat, Dr. Apinun Buritatum, and other staff at the Center of Excellence in Innovation for Sustainable Infrastructure Development, Suranaree University of Technology. I also wish to thank all the staff and faculty members as well as friends at the School of Civil Engineering, Suranaree University of Technology for the academic, administrative, and technical support during my Ph.D. study.

I would be remiss in not mentioning my superiors and colleagues in Faculty of Geography - Geology, University of Sciences - Hue University, Vietnam for their facilitation and encouragement during my Ph.D. study period.

Last but not least, I would like to thank my family for their love, understanding, and supporting me spiritually throughout my Ph.D. study and life.

Tran Thi Ngoc Quynh

TABLE OF CONTENTS

Page

ABSTRACT (THAI) I
ABSTRACT (ENGLISH) III
ACKNOWLEDGEMENT VI
TABLE OF CONTENTS VIII
LIST OF TABLES XI
LIST OF FIGURES XII
SYMBOLS AND ABBREVIATIONS XVII
CHAPTER
1 INTRODUCTION 1
1.1 Background 1
1.2 Problem statement 3
1.3 Significance of study 6
1.4 Research objectives and scope 7
1.5 Organization of thesis 8
1.6 References 9
2 LITERATURE REVIEW 16
2.1 Introduction 16
2.2 Recycled materials and applications 16
2.2.1 Steel slag 17
2.2.2 Recycled concrete aggregate 26
2.3 Natural rubber latex in pavement applications 34
2.4 Properties of cement stabilized materials and related Pavement performance 36
2.4.1 Strenth and modulus of cement stabilized layers and related pavement performance 37

2.4.2 Shrinkage of cement stabilized materials and related pavement distress 38
2.4.3 Fatigue of Cement stabilized layer related to pavement distress 39
2.4.4 Wetting-Drying durability of CSL 40
2.5 References 41
3 IMPROVED MECHANICAL AND MICROSTRUCTURE OF CEMENT-STABILIZED LATERITIC SOIL USING RECYCLED MATERIALS REPLACEMENT AND NATURAL RUBBER LATEX FOR PAVEMENT APPLICATIONS 52
3.1 Introduction 52
3.2 Materials and methods 56
3.2.1 Materials 56
3.2.2 Mix design 59
3.2.3 Experimental program 61
3.3 Results and discussion 64
3.3.1 Compaction characteristics 64
3.3.2 Unconfined compressive strength 65
3.3.3 Indirect tensile strength 70
3.3.4 Microstructural analysis 75
3.4 Conclusions 79
3.5 References 81
4 IMPROVED FATIGUE PROPERTIES OF CEMENT-STABILIZE RECYCLED MATERIALS - LATERITIC SOIL USING NATURAL RUBBER LATEX FOR SUSTAINABLE PAVEMENT APPLICATIONS 89
4.1 Introduction 89
4.2 Materials and methods 92
4.2.1 Materials 92
4.2.2 Samples preparation 93
4.2.3 Laboratory experimental program 95
4.3 Results and discussion 97

4.3.1 Mechanical strength 97
4.3.2 Indirect tensile resilient modulus (IT Mr) 99
4.3.3 Indirect tensile fatigue life 103
4.3.4 Permanent deformation and fatigue model 110
4.4 Conclusions 115
4.5 References 116
5 WETTING-DRYING DURABILITY PERFORMANCE OF CEMENT-STABILIZED RECYCLED MATERIALS AND LATERITIC SOIL USING NATURAL RUBBER LATEX FOR SUSTAINABLE PAVEMENT MATERIALS 124
5.1 Introduction 124
5.2 Materials and methods 127
5.2.1 Materials 127
5.2.2 Samples preparation 129
5.2.3 Experimental procedures 130
5.3 Results and discussion 131
5.3.1 Unconfined compressive strength 131
5.3.2 Durability against wetting-drying cycles 133
5.3.3 Microstructure changes 142
5.4 Conclusion 144
5.5 References 146
6 CONCLUSIONS AND RECOMMENDATIONS 153
6.1 Summary and conclusions 153
6.2 Recommendation for future works 156
APPENDIX
APPENDIX A. List of publications 159
BIOGRAPHY 184

LIST OF TABLES

Tables Page

2.1 Chemical compositions of Steel slag 18
2.2 Typical mineralogical compositions of steel slag 19
3.1 Physical and chemical properties of Portland cement 57
3.2 Properties of Natural Rubber Latex (NRL) 58
3.3 Engineering properties of SS, RCA and LS 58
3.4 Chemical compositions of LS, SS, and RCA 59
3.5 The ingredient and name of the studied mix design in this study 60
4.1 The ingredient of mixed design in this study 94

LIST OF FIGURES

Figures Page

2.1 Illustrative schemas for BOF and EAF slags 17
2.2 Fatigue life of mixes with different proportions of aggregates 23
2.3 Resilient modulus (a) and permanent deformation (b) of mixes with different proportions of aggregates 23
2.4 Plasticity index (a.) and free swell (b.) of high plastic subgrade soil samples using additive of fine SS 24
2.5 UCS and CBR of samples with various fine SS additive contents 24
2.6 Soaked CBR and Swelling of LS:SS blends at different compaction energy 25
2.7 SEM images show the amount of hydration product in samples with/without SS 26
2.8 Concrete compressive strength at different water-to-cement (w/c) ratios and different RCA contents 28
2.9 Splitting tensile strength of RCA and NA concretes with varied conditions of aggregate size, w/c ratio, and dry mix time 29
2.10 7-day cured UCS and ITS of cement stabilized RCA:VA and RAP:VA blends at different cement content 30
2.11 The elastic modulus of cement stabilized RCA:VA and RAP:VA blends at different cement content 31
2.12 UCS values of cement stabilized RCA and cement-PVA stabilized RCA at 7-day and 28-day cured times 32
2.13 UCS (a.) and ITS (b.) of cement stabilized RCA:NA with different RCA replacements at different cured times 33
2.14 Total amount of drying shrinkage and the dry shrinkage development with time cement stabilized RCA:NA with different RCA replacements 33

LIST OF FIGURES (Continued)

2.15 The microstructure of NRL-concrete for w/c = 0.4 at (a) r/c = 0; (b) r/c = 1.16 (optimal); (c) r/c = 5.78 35
2.16 Variation of water absorption, compressive strength, weight loss, and thermal conductivity of laterite soil-cement blocks corresponding NRL contents 36
2.17 Dry-shrinkage strain and Dry-shrinkage coefficient of CSM 39
3.1 Particle grain size distribution 59
3.2 Photograph of (a) UCS samples in curing condition, (b) before and after UCS testing 62
3.3 Photograph of ITS samples 63
3.4 The illustration of compaction characteristics of mixtures 64
3.5 Unconfined compressive strength of unstabilized samples, cement- and cement-NRL stabilized SS:LS and RCA:LS samples at various r/c ratios 66
3.6 Stress-strain curves of cement and cement-NRL stabilized SS:LS samples: (a) SS:LS=70:30 and (b) SS:LS=50:50 68
3.7 Stress-strain curves of cement and cement-NRL stabilized RCA:LS samples: (a) RCA:LS=70:30 and (b) RCA:LS=50:50 69
3.8 Indirect tensile strength of cement- and cement-NRL stabilized SS:LS and RCA:LS samples at various r/c ratios 71
3.9 Relationship between 7-day and 28-day UCS of cement-NRL stabilized (a) SS:LS and (b) RCA:LS samples at different r/c ratios 72
3.10 Relationship between 7-day and 28-day ITS of cement-NRL stabilized (a) SS:LS and (b) RCA:LS samples at different r/c ratios 73
3.11 Relationship between ITS and UCS of cement-NRL stabilized (a) SS:LS and (b) RCA:LS samples 74
3.12 Scanning electron microscope images of cement stabilized and cement-NRL stabilized SS:LS and RCA:LS samples at ages of 28 days 76

LIST OF FIGURES (Continued)

3.13 X-ray diffraction patterns of cement stabilized and cement-NRL stabilized SS:LS and RCA:LS samples at ages of 28 days................................ 78
3.14 The variation of Ca/Si ratios of cement stabilized and cement-NRL stabilized SS:LS and RCA:LS at different dry rubber/cement ratios 79
4.1 Grain size distribution of LS, SS, and RCA 93
4.2 Photograph of cylindrical samples and testing equipment in this research 95
4.3 (a) Unconfined compressive strength, and (b) Indirect tensile strength of 28-day cement- and cement-NRL stabilized SS:LS and RCA:LS samples at different SS/RCA:LS replacements and dry rubber/cement (r/c) ratios 98
4.4 Indirect tensile resilient modulus of cement- and cement-NRL stabilized SS:LS and RCA:LS blends at different SS/RCA replacements and dry rubber/cement (r/c) ratios 99
4.5 Relationship between horizontal deformations and the number of cycles under repeated-load at 30% stress level of cement- and cement-NRL stabilized SS/RCA:LS blends at optimum r/c ratio: (a) SS:LS=70:30, (b) SS:LS=50:50, (c) RCA:LS=70:30, and (d) RCA:LS=50:50. .... 102; 103
4.6 The schematic plot of the relationship between horizontal deformation and the number of cycles.. 104
4.7 Relationship between the number of cycles and horizontal deformation under fatigue test at 70% stress level: (a) cement- and cement-NRL stabilized SS:LS blends, (b) cement- and cement-NRL stabilized RCA:LS blends at different r/c ratios 106
4.8 Fatigue life (Fn) of cement- and cement-NRL stabilized SS:LS and RCA:LS blends at different SS/RCA replacements and r/c ratios.................... 107

LIST OF FIGURES (Continued)

4.9 Relationship between horizontal deformations and the number of cycles under repeated-load at 70% stress level of cement- and cement-NRL stabilized SS/RCA:LS blends at optimum r/c ratio: (a) SS:LS=70:30, (b) SS:LS=50:50, (c) RCA:LS=70:30, (b) and (d) RCA:LS=50:50 .... 108; 109

4.10 Relationship between UCS and ITS of SS:LS (a) and RCA:LS (b) samples at different r/c ratios 111

4.11 Relationship between ITS and IT M_r of SS:LS (a) and RCA:LS (b) samples at different r/c ratios 112

4.12 Relationship between IT M_r and Fatigue life of SS:LS (a) and RCA:LS (b) samples at different r/c ratios 113

4.13 Relationship between Fatigue life and Permanent deformation of SS:LS (a) and RCA:LS (b) samples at different r/c ratios 114

5.1 Grain size distribution of studied mixes 128

5.2 The procedure of one wetting - drying cycle 131

5.3 7-day and 28-day unconfined compressive strength of cement-NRL stabilized SS:LS=70:30, SS:LS=50:50, RCA:LS=70:30, and RCA:LS=50:50 samples at 0%, 3%, 5%, and 10% of r/c ratios 132

5.4 UCS of cement-NRL stabilized (a) SS:LS blends and (b) RCA:LS blends at various r/c ratios and different target w-d cycles of 1, 3, 6, 9, 12, and 15 135

5.5 $UCS_{w\text{-}d}$ percentage growth of cement-NRL stabilized SS:LS and RCA:LS samples at 3^{rd} and 15^{th} w-d cycles 136

5.6 The weight loss of cement-NRL stabilized (a) SS:LS blends and (b) RCA:LS blends at different number of w-d cycles 137

5.7 The water absorption of cement-NRL stabilized (a) SS:LS blends and (b) RCA:LS blends at different number of w-d cycles 138

5.8 Photos of cement-NRL SS:LS=70:30 samples at (a) r/c ratio of 0% and (b) r/c ratio of 3% at 1^{st}, 3^{rd}, and 15^{th} w-d cycles 139

LIST OF FIGURES (Continued)

5.9 Photos of cement-NRL RCA:LS=70:30 samples at (a) r/c ratio of 0% and (b) r/c ratio of 5% at 1st, 3rd, and 15th w-d cycles 140
5.10 SEM images of cement-NRL stabilized SS:LS=70:30 at (a) r/c ratio = 0% and (b) r/c ratio = 3% at 1st, 3rd, 6th, and 15th cycles 143
5.11 SEM images of cement-NRL stabilized RCA:LS=70:30 at (a, b) r/c ratio = 0% and (c, d) r/c ratio = 5% after 15 number of w-d cycles.. 144

SYMBOLS AND ABBREVIATIONS

%	=	Percentage
AASHTO	=	American Association of State Highway and Transportation official
Al_2O_3	=	Aluminum oxide
ASTM	=	American Society for Testing and Material
BS	=	British Standards
BS-EN	=	British Standards – European Norm
BOF	=	Basic oxygen furnace
C&D	=	Construction and Demolition
C_2S	=	Belite, Dicalcium silicate ($2CaO.SiO_2$)
C_3S	=	Alite, Tricalcium silicate ($3Ca.SiO_2$)
C_4AF	=	Ferrite, Tetracalcium aluminoferrite
$CaCO_3$	=	Calcium carbonate, Calcite
$CaMg(CO_3)_2$	=	Dolomite
CaO	=	Calcium oxide
CB	=	Crushed brick
CBR	=	California Bearing Ratio
CH	=	Portlandite, Calcium hydroxide ($Ca(OH)_2$)
cm^3	=	Cubic centimeter
CSM	=	Cement-stabilized materials
CSL	=	Cement-stabilized layer
C-S-H	=	Calcium-Silicate-Hydrate ($CaO-SiO_2-H_2O$)
DOH	=	Department of Highway
EDS	=	Energy Dispersive X-ray Spectrometer
Fe_2O_3	=	Iron oxide
g/cm^3	=	Gram per cubic centimeter
G_s	=	Specific gravity

SYMBOLS AND ABBREVIATIONS (Continued)

GBFS	=	Granulated blast-furnace slag
GW	=	Well-graded gravel
HMA	=	Hot-mix asphalt
in	=	Inch
IT M_r	=	Indirect tensile resilient modulus
ITF	=	Indirect tensile fatigue
ITFL	=	Indirect tensile fatigue life
ITFI	=	Indirect tensile initial fatigue
ITS	=	Indirect tensile strength
kPa	=	Kilopascal
L	=	Lime stone
LA	=	Los Angeles abration
LS	=	Lateritic soil
MDD	=	Maximum dry density
Mg/m^3	=	Megagram per cubic meter
MgO	=	Magnesium oxide
mm	=	Millimeter
M_r	=	Resilient modulus
MnO	=	Manganese oxide
MPa	=	Megapascal
NA	=	Natural aggregates
Na_2O	=	Sodium oxide
NRL	=	Natural rubber latex
°C	=	Degrees Celsius
OLC	=	Optimum liquid content
OWC	=	Optimum water content
pH	=	Potential of hydrogen
psi	=	Pound per square inch

SYMBOLS AND ABBREVIATIONS (Continued)

r/c	=	Dry rubber-to-cement ratio
RAP	=	Reclaimed asphalt pavement
RCA	=	Recycled concrete aggregate
SEM	=	Scanning electron microscope
SiO_2	=	Silicon dioxide, Quartz
SO_3	=	Sulfur trioxide, Sulfite
TiO_2	=	Titanium dioxide
SS	=	Steel slag
UCS	=	Unconfined compressive strength
USCS	=	Unified soil classification system
UTM	=	The universal testing machine
w-d	=	Wetting and drying cycles
XRD	=	X-Ray Diffraction
XRF	=	X-ray fluorescence
α	=	Alpha
β	=	Beta
γ	=	Gamma
θ	=	Theta

CHAPTER 1

INTRODUCTION

1.1 Background

Thailand is recognized as one of the developing countries with the fastest and strongest growth in Southeast Asia and in the world. The achievement in process of national economic expansion is significantly contributed by the continuous development of infrastructure, especially the transportation system. Within the road infrastructure construction progress, a remarkable expansion in the use of high-quality natural materials is inevitable. Hence, a vast amount of natural material needs to be exploited to provide construction, which causes negative influences on the environment and makes natural materials increasingly scarce.

The use of local material sources is always encouraged to minimize construction costs. However, some types of road construction have high-quality requirements that some natural materials available nearby the construction site cannot meet, requiring more extracting or transporting materials from other areas for alternative use. The use of supporting machinery equipment to exploit and transport materials not only significantly increase the construction cost but also contributes to increasing the carbon footprint in traffic construction. This is a worldwide problem which is the motivation as well as the challenge that forces scientists and national governments around the world to look for alternative construction materials.

Nowadays, research on sustainable alternative materials for use in construction is at the forefront trend that is concerned and encouraged in many countries around the world. One of the sustainable alternative materials ideas is using recycled materials (Hendriks & Janssen, 2003; Patil & Patil, 2017; Umar, Khamidi, & Tukur, 2014). Industrial by-products and construction and demolition (C&D) waste are generally called recycled materials, which are recognized as effective alternative materials to complement the use of natural materials and thus increasingly used in many countries all over the world. In recent decades, many researchers studied using recycled aggregates as pavement construction materials indicated that the replacement of recycled aggregates with different contents can be used in pavement applications, which demonstrated not only achieving the engineering construction requirements but also giving environmental and economic benefits (Arulrajah, Perera, Wong, Horpibulsuk, & Maghool, 2020; Chaurand et al., 2007; Disfani, Arulrajah, Bo, & Hankour, 2011; Ebrahim Abu El-Maaty Behiry, 2013; Hoy, Horpibulsuk, Rachan, Chinkulkijniwat, & Arulrajah, 2016; Imteaz, Arulrajah, & Maghool, 2020; Maghool, Arulrajah, Du, Horpibulsuk, & Chinkulkijniwat, 2016).

Besides researching and applying recycled materials in construction for natural materials replacement to reduce the environmental burden, the improving techniques of mechanical properties of materials are also widely studied to meet the increasing requirement of pavement constructions. The techniques for improving soil properties can be classified into three categories: physical, mechanical, and chemical methods. Typically, physical and mechanical methods are applied before resorting to the chemical method to minimize the input amount of additives required to achieve desired mechanical properties. Physical and mechanical stabilization methods involve mixing soils with high-quality coarse materials with an appropriate grain size distribution to enhance the interlocking between fine and coarse particles. Chemical stabilization methods use single or combined additives to improve material properties, which are commonly used in road applications and have been extensively researched. The use of combined additives not only improves the mechanical properties but also alleviates the shortcoming of material blends, which were indicated in many recent studies (Arulrajah, Mohammadinia, Phummiphan, Horpibulsuk, & Samingthong, 2016; Baghini, Ismail, Naseralavi, & Firoozi, 2016; Diab, Elyamany, & Ali, 2013; Hoy, Horpibulsuk, & Arulrajah, 2016; Komnitsas, Zaharaki, Vlachou, Bartzas, & Galetakis, 2015; Sukmak et al., 2020; Vásquez, Cárdenas, Robayo, & de Gutiérrez, 2016; Vo & Plank, 2018; Yaowarat et al., 2020).

To demonstrate the effectiveness of using recycled materials as well as additives in pavement applications and contribute research results to the construction guideline system which is still not completed due to laboratory investigation limitations, the improved blends of natural and recycled materials using additives are being extensively researched. Their performance is investigated via laboratory evaluation to ensure meeting the specification requirements.

1.2 Problem statement

In recent decades, climate change has been a topic of great interest for many researchers due to the undeniable evidence linking it to greenhouse gas emissions, particularly CO_2 (DCLG, 2006). In construction, several arguments suggest that the built environment significantly contributes to global climate change concerning CO_2 emissions, water consumption, landfill waste, and used raw materials (BERR, 2008). In addition, construction and industrial waste are becoming an environmental burden in many industrial cities of developed and developing countries around the world. A large amount of waste material such as steel slag (SS) and recycled concrete aggregate (RCA) is being created from human activities such as industry, commercial, and construction & demolition each year. SS is the by-product of the steel-making industry, which is becoming increase due to the growth of steel manufacturing. It is projected that the steel industry in Thailand annually supplies 1.5 million tons of steel slag as a by-product of steel manufacture (Sudla et al., 2018). RCA is the aged product of concrete aggregates, bricks, glass, gypsums, and ceramics, which are demolished from old concrete pavements and buildings reaching their own service life. In Thailand, the construction industry produces around 1.1 million tonnes of waste, with over 50% of this waste being concrete (Manowong & Brockmann, 2015). These materials were previously considered worthless and disposed of as waste which is an environmental burden, while the rapidly increasing quality and quantity demand of road construction has led to the overexploitation of natural construction material, resulting in the scarcity of natural material sources. With awareness and the environmental problem of waste materials, many governments and researchers around the world attempt to divert these wastes from landfills into sustainable construction materials. Their effort has been proven by a vast of studies conducted with the expectation of effective application of waste materials in pavement construction (Arulrajah et al., 2016; Arulrajah et al., 2020; Disfani et al., 2011; Imteaz, Ali, & Arulrajah, 2012; Mohammadinia, Arulrajah, Horpibulsuk, & Chinkulkijniwat, 2017; Phummiphan et al., 2018); (Barišić, Dimter, & Rukavina, 2015; Ebrahim Abu El-Maaty Behiry, 2013; Hoy, Horpibulsuk, & Arulrajah, 2016; Maslehuddin, Sharif, Shameem, Ibrahim, & Barry, 2003; Qasrawi, Shalabi, & Asi, 2009).

Waste materials can fully and/or partially substitute for natural materials not only offering positive environmental effects but also reducing the natural materials shortage and improving the properties of pavement structures. In order to be used for pavement purposes, the materials must satisfy the specific requirements of international and local construction authorities (Sherwood, 2001) while most of recycled materials classify and properties do not meet the specification requirements. Hence, different improvement techniques are considerably employed to improve properties of materials. Portland cement possesses the ability to rapidly enhance mechanical properties of the material and the ease of application in the field (Horpibulsuk et al. 2006; Horpibulsuk et al. 2010), it is thus the common chemical method used in the improvement of materials. Sobhan and Das (2007) indicated that the hydration products in cement-stabilized samples improved the interparticle bonding and hence enhanced the strength of cement-stabilized materials. Arora and Aydilek (2005) and (Buritatun et al., 2022a; 2020) also reported that increasing the cement content resulted in higher values of UCS and resilient modulus. Stabilized pavement bases act as a stiff layer that distributes the traffic loads over a larger area, reducing the stress on the subgrade and preventing the formation of ruts and other forms of pavement distress. This preserves the original grade for many years and extends the service life of pavement without expensive resurfacing or repairs (Christopher, Schwartz, & Boudreau, 2006). Longer fatigue life for the asphalt surface is achieved by the higher stiffness of cement stabilized bases, which results in reduced pavement deflections and lower asphalt stresses. The fatigue cracking is a significant cause of pavement failure, which is decreased by the application of cement stabilization. Though cement stabilization provides many advantages in improvement of materials for pavement applications, it also exhibites several shortcoming such as brittle behavior under compressive, tensile, and flexural stresses caused by traffic loads and internal temperature (Correia, Oliveira, & Custodio, 2015; Jamsawang, Voottipruex, & Horpibulsuk, 2015; Khattak & Alrashidi, 2006; Mengue, Mroueh, Lancelot, & Eko, 2017; Wahab et al., 2021; Yaowarat et al., 2021). Hence, Synthetic polymer additives have been used as the second additive to alleviate the limitations of cement stabilization. It is proved that the polymer additive can improve the ductivity of cement stabilization by enhancing the interparticle bonding strength within stabilizied structure (Newman, Tingle, Gill, & McCaffrey, 2005; Santoni, Tingle, & Webster, 2002; Tingle, Newman, Larson, Weiss, & Rushing, 2007; Tingle & Santoni, 2003).

Natural rubber latex (NRL) is a milky sap that is extracted from the Hevea brasiliensis tree and it is a biopolymer composed primarily of polyisoprene, a natural polymer that gives it its unique elastic and tensile properties. Its properties are particularly useful in applications where a high degree of flexibility, strength, and durability are required. Consequently, it has the potential to serve as an eco-friendly alternative additive in pavement applications. Its potential has been proved in improving the viscosity and elastic properties of asphalt (Wen, Wang, Zhao, & Sumalee, 2017), and the performance of cement-stabilized materials (Buritatun et al., 2022b; 2021; Buritatun et al., 2020; Dv, Hoy, Karntatam, Arulrajah, & Horpibulsuk, 2022) by forming the rubber films and filling the pore space within the stabilized matrix, leading to a stronger stabilized structure. However, the performances of materials are improved by the appropriate amount of NRL (optimum NRL content). Beyond this optimum, the strength of materials tends to decrease because the excess NRL creates a thicker film covering the aggregate-cement matrix and retarded the hydration process. The optimum NRL contents are different for diverse material blends and cement contents. For instance, Buritatun et al. (2020) report that the highest unconfined compressive and flexural strengths of cement-NRL stabilized soil were obtained when 20%, 15%, and 10% NRL additive replacement of cement by weight for the samples with 3%, 5%, and 7% cement contents, respectively. For the cement-stabilized recycled concrete aggregate, Dv et al. (2022) found that the highest unconfined compressive strength and tensile strength values of cement-NRL stabilized recycled concrete aggregate were achieved when using optimum r/c ratios of 10%, 5%, and 5% for samples containing 3%, 5%, and 7% cement, respectively. Therefore, the NRL application in pavement construction should be researched for different materials.

Thailand is a major producer of NRL on a global scale. Besides exporting, the Thailand government promotes research and development in using NRL for civil construction purposes, particularly for pavements as the rapidly expanding road network. NRL is an eco-friendly additive innovation that can enhance the effectiveness of cement-stabilized materials and is therefore an option for sustainable construction. To the best author's knowledge, there has been no previous study on the use of NRL as a polymer to enhance the performance of cement-stabilized lateritic soil with recycled aggregate replacement as pavement materials. Therefore, the objective of this research is to explore the potential of NRL in improving the performance of cement-stabilized lateritic soil and recycled materials. The findings of this study will encourage the use of NRL as an eco-friendly alternative additive in cement-stabilized materials not only in Thailand but also in other countries.

1.3 Significance of study

This research will offer new insights into the improved performance of cement-stabilized lateritic soil for pavement base purposes. This is achieved through using recycled materials substitution and natural rubber latex.

By comparing mechanical properties of the samples at various content of recycled aggregate replacements and different dry rubber-to-cement ratios, the current understanding of the potential of using recycled aggregates to improve unfavorable characteristics of lateritic soil, such as excessive plasticity, substandard gradation, and low tensile strength, will be expanded to meet the requirements for high-volume roads specified by local or international road authorities. The research will also aim at improving the shortcoming of cement-stabilized materials such as brittle behavior as well as the durability of cement stabilization by using natural rubber latex.

Specifically, this research will investigate the variation in terms of strengths, durability against wetting-drying cycles, and fatigue failure of cement stabilized materials under several influent factors such as steel slag:lateritic soil (SS:LS) ratios, recycled concrete aggregate:lateritic soil (RCA:LS) ratios, dry rubber:cement (r/c) ratios.

The application of recycled materials in pavement application also contributes to solving the environmental burden due to the increasing recycled materials such as steel slag and RCA in the current situation of the growth of steel manufacture and construction demolition while natural materials are increasingly becoming scarce.

With similar elastic and tensile properties to synthetic polymer additives, NRL is recognized as a "green" additive to improve microstructure and mechanical properties of cement stabilized materials alternate to Synthetic polymer additives.

1.4 Research objectives and scope

The large increasing amount of annually created recycled materials such as SS and RCA cause an environmental burden while the potential of using these materials can meet the urgent demand for construction materials, SS and RCA are researched as an alternative aggregate in a mixture with lateritic soil which improved by using combined additives including cement and natural rubber latex as pavement base materials. A laboratory investigation has to be conducted to evaluate the effect of the NRL and the replacement of SS and RCA with LS on the performance of cement-stabilized soil.

This study is limited to the effectiveness of utilizing cement-NRL stabilized recycled aggregates and lateritic soil as sustainable pavement base materials for road construction. The research focuses on geotechnical laboratory experimental programs aimed at clarifying the practical usage of NRL in the improvement of cement-stabilized recycled materials and lateritic soil with different recycled aggregates (SS/RCA) replacement ratios and various r/c ratios.

The three main objectives of this research are to address as the following outline:

- To investigate the potential of using recycled materials and NRL on the mechanical properties and microstructure improvements of cement-stabilized lateritic soil for pavement applications.
- To assess the resilient modulus and fatigue life of cement-NRL stabilized recycled aggregates-lateritic soil as the structural distress considered in the thickness design process for the stabilized base layer.
- To evaluate the influence of wetting-drying cycles on the compression strength and microstructure of cement-NRL Steel slag/Recycled concrete aggregate-lateritic soil at different replacement ratios of SS/RCA.

1.5 Organization of thesis

This thesis is composed of six chapters, the summaries of each chapter are outlined as follows:

Chapter I is the introduction part that includes the background, the problem statement, the significance of study, the objectives and scope, and the thesis organization.

Chapter II presents the literature review of recent research papers involves with the engineering properties and applications of natural rubber latex and recycled materials including steel slag and recycled concrete aggregate in pavement construction. Stabilized materials and related pavement performance were also included in this chapter.

Chapter III presents the study of the improved mechanical and microstructure of cement-stabilized lateritic soil using recycled materials replacement and natural rubber latex for pavement applications. The basic engineering properties of LS, SS, RCA materials, and cement and NRL additives are presented. Besides, the study focussed on the mechanical strengths development and microstructure change of cement-stabilized lateritic soil under various influent factors including steel slag-to-lateritic soil (SS:LS) ratios, recycled concrete aggregate-to-lateritic soil (RCA:LS) ratios, and dry rubber-to-cement (r/c) ratios.

Chapter IV presents the study of fatigue properties of cement-NRL stabilized recycled materials and lateritic soil blends at various r/c ratios under cyclic loading conditions. This chapter aims to assess the role of NRL additive in improving the resilient modulus, fatigue life, and permanent deformation resistance of cement stabilized SS:LS and RCA:LS blends at different SS/RCA replacement ratios and stress levels. The mechanistic and fatigue models of cement-NRL stabilized recycled materials and lateritic soil blends were also proposed in this chapter, which is important in the mechanistic-empirical (M-E) pavement design approach and useful in use as the essential parameter for numerical modeling in M-E models.

Chapter V shows an investigation of wetting-drying (w-d) cycles test on the 28-day cement-NRL stabilized SS:LS and RCA:LS samples to assess the potential of NRL additive on w-d resistance of cement stabilized SS:LS and RCA:LS blends under the influence of recycled materials (SS/RCA) to lateritic soil ratios, r/c ratios, and w-d cycles. The $UCS_{w\text{-}d}$, weight loss, water absorption, and microstructural change were considered as the results of the w-d cycles test and presented in this chapter.

Chapter VI concludes the research work and provides suggestions as well as recommendations for further study.

1.6 References

Arora, S., & Aydilek, A. H. (2005). Class F Fly-Ash-Amended Soils as Highway Base Materials. *Journal of Materials in Civil Engineering, 17*, 640-649. doi:10.1061/(ASCE)0899-1561(2005)17:6(640)

Arulrajah, A., Mohammadinia, A., Phummiphan, I., Horpibulsuk, S., & Samingthong, W. (2016). Stabilization of Recycled Demolition Aggregates by Geopolymers comprising Calcium Carbide Residue, Fly Ash and Slag precursors. *Construction and Building Materials, 114*, 864-873. doi:10.1016/j.conbuildmat.2016.03.150

Arulrajah, A., Perera, S., Wong, Y. C., Horpibulsuk, S., & Maghool, F. (2020). Stiffness and flexural strength evaluation of cement stabilized PET blends with demolition wastes. *Construction and Building Materials, 239*. Doi: 10.1016/j.conbuildmat. 2019.117819

Baghini, M. S., Ismail, A., Naseralavi, S. S., & Firoozi, A. A. (2016). Performance evaluation of road base stabilized with styrene–butadiene copolymer latex and Portland cement. *Pavement research and technology, 9*, 321-336. Doi: 10.1016/j.ijprt. 2016.08.006

Barišić, I., Dimter, S., & Rukavina, T. (2015). Elastic properties of cement-stabilised mixes with steel slag. *International Journal of Pavement Engineering, 17*(9), 753-762. doi:10.1080/10298436.2015.1019496

BERR. (2008). Strategy for sustainable construction. *London: Department for Business, Enterprise and Regulatory Reform, HM Government.*

Buritatun, A., Aiamsri, K., Yaowarat, T., Suddeepong, A., Horpibulsuk, S., Arulrajah, A., & Kou, H. (2022b). Improved Fatigue Performance and Cost-Effectiveness of Natural Rubber Latex–Modified Cement-Stabilized Pavement Base at Raised Temperatures. *Journal of Materials in Civil Engineering, 35*(3). Doi: 10.1061/ (ASCE)MT.1943-5533.0004637

Buritatun, A., Horpibulsuk, S., Udomchai, A., Suddeepong, A., Takaikaew, T., Vichitcholchai, N., . . . Arulrajah, A. (2021). Durability improvement of cement stabilized pavement base using natural rubber latex. *Transportation Geotechnics, 28*. Doi: 10.1016/j.trgeo.2021.100518

Buritatun, A., Suddeepong, A., Horpibulsuk, S., Udomchai, A., Arulrajah, A., Mohammadinia, A., . . . Hoy, M. (2022a). Improvement of Tensile Properties of Cement-Stabilized Soil Using Natural Rubber Latex. *Journal of Materials in Civil Engineering, 34*(4). Doi: 10.1061/(ASCE)MT.1943-5533.0004173

Buritatun, A., Takaikaew, T., Horpibulsuk, S., Udomchai, A., Hoy, M., Vichitcholchai, N., & Arulrajah, A. (2020). Mechanical Strength Improvement of Cement-Stabilized

Soil Using Natural Rubber Latex for Pavement Base Applications. *Materials in Civil Engineering, 32*(12). Doi: 10.1061/(ASCE)MT.1943-5533.0003471

Chaurand, P., Rose, J., Briois, V., Olivi, L., Hazemann, J. L., Proux, O., . . . Bottero, J. Y. (2007). Environmental impacts of steel slag reused in road construction: a crystallographic and molecular (XANES) approach. *J Hazard Mater, 139*(3), 537-542. Doi: 10.1016/j.jhazmat.2006.02.060

Christopher, B., Schwartz, C., & Boudreau, R. (2006). Geotechnical Aspects of Pavements Reference Manual. *Federal Highway Administration, Woodbury*.

Correia, A. A. S., Oliveira, P. J. V., & Custodio, D. G. (2015). Effect of polypropylene fibres on the compressive and tensile strength of a soft soil, artificially stabilised with binders. *Geotextiles and Geomembranes, 43*(2), 97-106. Doi: 10.1016/j.geotexmem.2014.11.008

DCLG. (2006). Builidng A greener future: Towards Zero Carbon Development. *Department for Communities and Local Government*.

Diab, A. M., Elyamany, H. E., & Ali, A. H. (2013). Experimental investigation of the effect of latex solid/water ratio on latex modified co-matrix mechanical properties. *Alexandria Engineering Journal, 52*(1), 83-98. Doi: 10.1016/j.aej.2012.11.002

Disfani, M. M., Arulrajah, A., Bo, M. W., & Hankour, R. (2011). Recycled crushed glass in road work applications. *Waste Manag, 31*(11), 2341-2351. Doi: 10.1016/j.wasman.2011.07.003

Dv, N., Hoy, M., Karntatam, K., Arulrajah, A., & Horpibulsuk, J. (2022). Cement – natural rubber latex stabilised recycled concrete aggregate as a pavement base material. *Road Materials and Pavement Design*, 1-15. Doi: 10.1080/14680629.2022.2072755

Ebrahim Abu El-Maaty Behiry, A. (2013). Utilization of cement treated recycled concrete aggregates as base or subbase layer in Egypt. *Ain Shams Engineering, 4*(4), 12. Doi: 10.1016/j.asej.2013.02.005

Hendriks, C. F., & Janssen, G. M. T. (2003). Use Of Recycled Materials In Constructions. *Materials and Structures, 36*, 604-608.

Hoy, M., Horpibulsuk, S., & Arulrajah, A. (2016). Strength development of Recycled Asphalt Pavement – Fly ash geopolymer as a road construction material.

Construction and Building Materials, 117, 209-219. Doi: 10.1016/j.conbuildmat. 2016.04.136

Hoy, M., Horpibulsuk, S., Rachan, R., Chinkulkijniwat, A., & Arulrajah, A. (2016). Recycled asphalt pavement – fly ash geopolymers as a sustainable pavement base material: Strength and toxic leaching investigations. *Science of the Total Environment, 573*, 19-26. Doi: 10.1016/j.scitotenv.2016.08.078

Imteaz, M. A., Ali, M. M., & Arulrajah, A. (2012). Possible environmental impacts of recycled glass used as a pavement base material. *Waste Manag Res, 30*(9), 917-921. Doi: 10.1177/0734242X12448512

Imteaz, M. A., Arulrajah, A., & Maghool, F. (2020). Environmental and geotechnical suitability of recycling waste materials from plasterboard manufacturing. *Waste Manag Res, 38*(4), 383-391. Doi: 10.1177/0734242X19881213

Jamsawang, P., Voottipruex, P., & Horpibulsuk, S. (2015). Flexural Strength Characteristics of Compacted Cement-Polypropylene Fiber Sand. *Journal of Materials in Civil Engineering, 27*(9). Doi: 10.1061/(asce)mt.1943-5533.0001205

Khattak, M. J., & Alrashidi, M. (2006). Durability and mechanistic characteristics of fiber reinforced soil-cement mixtures. *Pavement Engineering, 7*(1), 53-62. Doi: 10.1080/10298430500489207

Komnitsas, K., Zaharaki, D., Vlachou, A., Bartzas, G., & Galetakis, M. (2015). Effect of synthesis parameters on the quality of construction and demolition wastes (CDW) geopolymers. *Advanced Powder Technology, 26*(2), 368-376. Doi: 10.1016/j.apt.2014.11.012

Maghool, F., Arulrajah, A., Du, Y.-J., Horpibulsuk, S., & Chinkulkijniwat, A. (2016). Environmental impacts of utilizing waste steel slag aggregates as recycled road construction materials. *Clean Technologies and Environmental Policy, 19*(4), 949-958. Doi: 10.1007/s10098-016-1289-6

Manowong, E., & Brockmann, C. (2015). Construction Waste Management in Newly Industrialized Countries. http://www.irbnet.de/daten/iconda/CIB_DC24555.pdf.

Maslehuddin, M., Sharif, A. M., Shameem, M., Ibrahim, M., & Barry, M. S. (2003). Comparison of properties of steel slag and crushed limestone aggregate concretes. *Construction and Building Materials, 17*, 105-112.

Mengue, E., Mroueh, H., Lancelot, L., & Eko, R. M. (2017). Mechanical Improvement of a Fine-Grained Lateritic Soil Treated with Cement for Use in Road Construction. *Journal of Materials in Civil Engineering, 29*(11). Doi: 10.1061/(asce)mt.1943-5533.0002059

Mohammadinia, A., Arulrajah, A., Horpibulsuk, S., & Chinkulkijniwat, A. (2017). Effect of fly ash on properties of crushed brick and reclaimed asphalt in pavement base/subbase applications. *J Hazard Mater, 321*, 547-556. Doi: 10.1016/j. jhazmat.2016.09.039

Newman, J. K., Tingle, J. S., Gill, C., & McCaffrey, T. J. (2005). Stabilization of Silty Sand Using Polymer Emulsions. *International Journal of Pavements, 4*.

Patil, K. M., & Patil, M. S. (2017). Sustainable construction materials and Technology in context with sustainable developemnt. *International Journal of Engineering Research and Technology, 10*(1), 112-117.

Phummiphan, I., Horpibulsuk, S., Rachan, R., Arulrajah, A., Shen, S. L., & Chindaprasirt, P. (2018). High calcium fly ash geopolymer stabilized lateritic soil and granulated blast furnace slag blends as a pavement base material. *J Hazard Mater, 341*, 257-267. Doi: 10.1016/j.jhazmat.2017.07.067

Qasrawi, H., Shalabi, F., & Asi, I. (2009). Use of low CaO unprocessed steel slag in concrete as fine aggregate. *Construction and Building Materials, 23*(2), 1118-1125. Doi: 10.1016/j.conbuildmat.2008.06.003

Santoni, R. L., Tingle, J. S., & Webster, S. L. (2002). Stabilization of Silty Sand with Nontraditional Additives. *Transportation Research Record, 1787*(1), 61-70. Doi: 10.3141/1787-07

Sherwood, P. T. (2001). Alternative Materials in Road Construction : A Guide to the Use of Recycled and Secondary Aggregates. Second edition. *London: Thomas Telford.*

Sobhan, K., & Das, B. M. (2007). Durabillity of soil cements against fatigue frature. *Journal of Materials in Civil Engineering, 19*(1), 26-32. Doi: 10.1061/(ASCE)0899-1561(2007)19:1(26)

Sudla, P., Horpibulsuk, S., Chinkulkijniwat, A., Arulrajah, A., Liu, M. D., & Hoy, M. (2018). Marginal lateritic soil/crushed slag blends as an engineering fill material. *Soils and Foundations, 58*. Doi: 10.1016/j.sandf.2018.03.007

Sukmak, G., Sukmak, P., Horpibulsuk, S., Yaowarat, T., Kunchariyakun, K., Patarapaiboolchai, O., & Arulrajah, A. (2020). Physical and mechanical properties of natural rubber modified cement paste. *Construction and Building Materials, 244*. Doi: 10.1016/j.conbuildmat.2020.118319

Tingle, J. S., Newman, J. K., Larson, S. L., Weiss, C. A., & Rushing, J. F. (2007). Stabilization Mechanisms of Nontraditional Additives. *Transportation Research Record, 1989-2*(1), 59-67. Doi: 10.3141/1989-49

Tingle, J. S., & Santoni, R. L. (2003). Stabilization of Clay Soils with Nontraditional Additives. *Transportation research board, 1819*(1). Doi: 10.3141/1819b-10

Umar, U. A., Khamidi, M. F., & Tukur, H. (2014). Sustainable building material for green building construction, conservation and refurbishing *Management in Construction Research Association (MiCRA), Postgraduate Conference*.

Vásquez, A., Cárdenas, V., Robayo, R. A., & de Gutiérrez, R. M. (2016). Geopolymer based on concrete demolition waste. *Advanced Powder Technology, 27*(4), 1173-1179. Doi: 10.1016/j.apt.2016.03.029

Vo, M. L., & Plank, J. (2018). Evaluation of natural rubber latex as film forming additive in cementitious mortar. *Construction and Building Materials, 169*, 93-99. Doi: 10.1016/j.conbuildmat.2017.12.098

Wahab, N. A., Roshan, M. J., Rashid, A. S. A., Hezmi, M. A., Jusoh, S. N., Nik Norsyahariati, N. D., & Tamassoki, S. (2021). Strength and Durability of Cement-Treated Lateritic Soil. *Sustainability, 13*(11). Doi: 10.3390/su13116430

Wen, Y., Wang, Y., Zhao, K., & Sumalee, A. (2017). The use of natural rubber latex as a renewable and sustainable modifier of asphalt binder. *International Journal of Pavement Engineering, 18*(6), 547-559. Doi: 10.1080/10298436.2015.1095913

Yaowarat, T., Horpibulsuk, S., Arulrajah, A., Maghool, F., Mirzababaei, M., Rashid, A. S. A., & Chinkulkijniwat, A. (2020). Cement stabilization of recycled concrete aggregate modified with polyvinyl alcohol. *International Journal of Pavement Engineering*. Doi: 10.1080/10298436.2020.1746311

Yaowarat, T., Suddeepong, A., Hoy, M., Horpibulsuk, S., Takaikaew, T., Vichitcholchai, N., . . . Chinkulkijniwat, A. (2021). Improvement of flexural strength of concrete pavements using natural rubber latex. *Construction and Building Materials, 282*. Doi: 10.1016/j.conbuildmat.2021.122704

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

The constitutions of pavement layers are typically constructed from high-quality materials, which are carefully selected to satisfy engineering requirements, following the standards for construction. High-quality materials might be natural aggregates including crushed rock and granular aggregate materials. In recent decades, the scarcity of natural construction materials is becoming an extreme problem. Hence, recycled materials including construction and demolition (C&D) waste and industrial by-products are being extensively investigated as potential substitute materials for use in construction, specifically for pavement applications. In addition, the mechanical properties and serviceability of materials have been studied using additives to lengthen the service life of pavements. Therefore, this chapter focuses on the literature related to the utilization of recycled construction materials such as Steel slag (SS) and recycled concrete aggregate (RCA), along with the use of natural rubber latex (NRL) additive in pavement applications, to improve their lifespan.

2.2 Recycled materials and applications

Sustainable materials are becoming top-researching in the construction industry. Recycling materials have been widely researched and utilized as a sustainable option for pavement applications to conserve natural resources and decrease the environmental burden. The objective of sustainable development is to diminish the negative impact of the construction industry on the environment, and the use of recycled aggregates has been demonstrated to address some of the drawbacks of natural materials. Due to growing concerns about the financial and environmental consequences of disposing of construction and industrial waste, the substitution of natural aggregates with RCA and SS has been attracting appreciable attention in the construction field. The interest in RCA and SS has been steadily rising as they are produced in the hundreds of millions of tonnes annually worldwide.

2.2.1 Steel slag

Steel slag (SS) is a by-product of the steel manufacturing industry that results from either converting iron to steel in a basic oxygen furnace (BOF) or melting scrap to produce steel in an electric arc furnace (EAF). To create SS, liquid impurities such as carbon monoxide, silicon, manganese, phosphorous, and iron are combined with lime and dolomite lime and separated by injecting oxygen with high pressure. Cold steel scrap is melted through a high electric current passing through graphite electrodes to form an arc. Other metals and alloys may be added to balance the chemical composition, and then oxygen is blown to purify the steel (Shi, 2004). The treatment process of SS involves four steps: separating and cooling the steel with air or water, crushing and grading the slag repeatedly until it meets the required aggregate gradation.

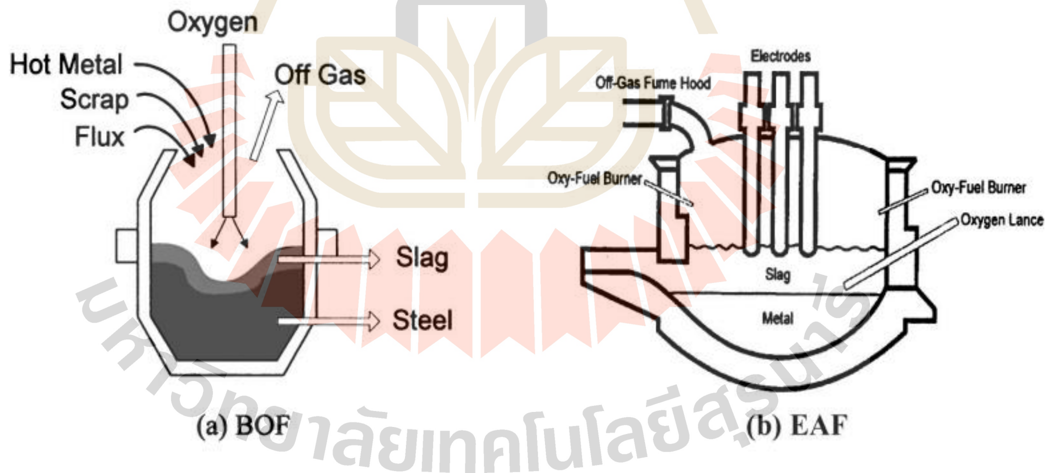


Figure 2.1. Illustrative schemas for BOF and EAF slags (Shi, 2004)

Large quantities of SS are manufactured in the steel industry, and it has been noted that SS can be used as a substitute for natural aggregates (NA), which are limited in the availability of high-performance aggregates. SS has distinct chemical and mineral composition properties that set it apart from NA and other recycled waste materials.

Table 2.1. Chemical compositions of Steel slag.

Reference	SS	CaO	SiO_2	Al_2O_3	FeO/Fe_2O_3	MgO	MnO	TiO_2	SO_3	P_2O_5	Free CaO
(Shen, Wu, & Du, 2009)	BOF	39.3	7.75	0.98	.../38.06	8.56	4.24	0.94	0.02	...	...
(Shi, 2004)	EAF	35-60	9-20	2-9	15-13/...	5-15	0-8	...	0.08-0.23	0.01-0.25	...
(Mahieux, Aubert, & Escadeillas, 2009)	BOF	47.5	11.8	2.0	.../22.6	6.3	1.9	0.5	...	2.7	...
(Chaurand et al., 2007)	BOF	41.3	12.5	2.4	.../31.2	4.3	6.1	0.8	...	1.1	...
(Motz & Geiseler, 2001)	EAF	25-40	10-17	4-7	.../...	4-15	<6	...	...	<1.5	<3
(Nicolae, Vilciu, & Zaman, 2007)	EAF	40.78	17.81	4.23	9.25/3.97	8.53	9.79	...	0.3	0.74	...
(Nicolae et al., 2007)	BOF	40.1	17.8	2.04	12.92/6.58	6.32	6.52	...	0.46	1.13	3.9
(Tossavainen et al., 2007)	EAF	45.5	32.2	3.7	3.3/1	5.2	2	...	...	...	...
(Lekakh, Rawlins, Robertson, Richards, & Peaslee, 2008)	EAF	32.1	19.4	8.6	.../...	9.4	6.8	0.4	0.6	...	...
(Poh, Ghataora, & Ghazireh, 2006)	BOF	41.44	15.26	4.35	13.95/9.24	8.06	5.2	0.72	...	1.15	3.9
(Tsakiridis, Papadimitriou, Tsivilis, & Koroneos, 2008)	EAF	35.7	17.53	6.25	.../26.36	6.45	2.5	0.76	...	...	...
(Xue, Wu, Hou, & Zha, 2006)	EAF	29.49	16.11	7.56	.../32.56	4.96	4.53	0.78	0.63	0.55	...
(Tossavainen et al., 2007)	BOF	45	11.1	1.9	10.7/10.9	9.6	3.1	...	...	...	...
(Manso, Polanco, Losañez, & González, 2006)	EAF	23.9	15.3	7.4	.../...	5.1	4.5	...	0.1	...	0.45
(Reddy, Pradhan, & Chandra, 2006)	EAF	52.3	15.3	1.3	.../...	1.1	0.39	...	...	3.1	10.0
(Luxán, Sotolongo, Dorrego, & Herrero, 2000)	EAF	24.4	15.35	12.21	34.36/...	2.91	5.57	0.56	...	1.19	...

a. Chemical and mineral composition

Generally, the main chemical compositions of SS consist of CaO, MgO, SiO_2, and FeO, which are recognized in the high content of about 88-90% (Table 2.1).

BOF and EAF slags share common features that are characterized by dicalcium silicate, dicalcium ferrite, and wustite. Dicalcium silicate has a stabilizing effect on SS disintegration. Studies have indicated that the presence of dissolved lime and MgO does not have an impact on SS volume. Nevertheless, an excessive amount of "spongy free lime" and MgO could result in volume instability (Ge&eler, 1996).

Table 2.2. Typical mineralogical compositions of steel slag.

References	SS	Mineralogical composition
(Barra, Ramonich, & Munoz, 2001; Xue et al., 2006)	EAF	$CaCO_3$, FeO, MgO, Fe_2O_3, Ca_2Al $(AlSiO_7)$, Ca_2SiO_4
(Luxán et al., 2000)	EAF	Ca_2SiO_5, Ca_2Al $(AlSiO_7)$, Fe_2O_3, $Ca_{14}Mg^2(SiO_4)_8$, $MgFe_2O_4$, Mn_3O_4, MnO_2
(Nicolae et al., 2007)	BOF	$2CaO.Al_2O_3.SiO_2$, Fe_2O_3, CaO, FeO
(Nicolae et al., 2007)	EAF	MnO_2, MnO, Fe_2SiO_4, Fe_7SiO_{10}
(Reddy et al., 2006)	BOF	$2CaO.Fe_2O_{32}CaO.P_2O_5$, $2CaO.SiO_2$, CaO
(Tossavainen et al., 2007)	BOF	β-Ca_2SiO_4, FeO-MnO-MgO solid solution MO
(Tossavainen et al., 2007)	EAF	Ca_3MgSiO_{42}, β-Ca_2SiO_4 spinal sollid solution $(Mg,Mn)(Cr,Al)_2O_4$ wsuite-type solid solution ((Fe,Mg,Mn)O), $Ca_2(Al,Fe)_2O_5$
(Tsakiridis et al., 2008)	EAF	Ca_2SiO_4,$4CaO.Al_2O_3.FeO_3$, $Ca_2Al(AlSiO_7)$, Ca_3SiO_5, $2CaO.Al_2O_3SiO_2$, FeO, Fe_3O_4, MgO, SiO_2

b. Physical and mechanical properties

The characteristics of SS regarding its physical and mechanical attributes are widely recognized that meet the requirements for top-quality material. Indeed, SS exhibits exceptional strength, impermeability, stability, abrasion resistance, cracking and fractures, and permanent deformation in comparison to natural materials (Aiban, 2006; Alizadeh et al., 2003; Pasetto & Baldo, 2011; Sofilic, Mladenovič, & Sofilič, 2011). SS is a heavy-weight material because of sufficient amounts of iron oxide included, the heavy-weight is presented by the great specific gravity lying within the range of 3-4.

SS is heavier than minerals such as limestone and granite about 20%. The particle size range of SS is from large to dust, which is dependent on the generation process in the steel mill. Grain size distribution is a crucial factor affecting the mechanical properties of the material. SS should be crushed and sieved until meeting the specific requirements of the applied field before use.

c. *Compaction characteristics*

Several studies have been performed on the compaction behavior of SS and SS-aggregates mixes. Most studies displayed similar results that were higher MDD values and lower OWC values compared with NA because of its higher specific gravity and lower water absorption (Andreas, Herrmann, Lidstrom-Larsson, & Lagerkvist, 2005; Rohde, Peres Núñez, & Augusto Pereira Ceratti, 2003; Sudla et al., 2019; Sudla et al., 2018). Sudla et al. (2018) indicated that SS with high abrasion resistance can improve particle breakage under compaction energy, resulting in lower fine content, higher soaked CBR, and lower swelling.

d. *Thermal properties*

Noureldin and McDaniel (1990) indicated that SS possesses heat retention property superior to NA, giving it the potential to preserve heat for extended periods, which is advantageous in producing hot mix asphalt concrete for coating aggregates, particularly when repairing pavement surfaces in cold weather.

e. *Steel slag in construction application*

The areas of reused SS may differ depending on the particular conditions of each area and plant. In construction, SS has been used as the raw material in cement manufacture, aggregate in bases/subbases materials, embankment, filling, and hot asphalt mixtures, which are common applications in recent times. The application of fine and/or coarse SS aggregates can enhance the performance of the structure.

The presence of C_3S, C_2S, and C_4AF indicates that SS has cement-like (or cementitious) properties. It is accepted that the cement-like properties of SS increase with its basicity. Therefore, finely-ground SS can be utilized as cement additives and concrete admixtures (Altun & Yılmaz, 2002; Guo & Shi, 2013; Huang & Lin, 2010; Tsakiridis et al., 2008). Altun and Yılmaz (2002) showed the addition of 30% SS fine powder into cement that qualified the Turkish standard requirements for Portland cement. Tsakiridis et al. (2008) studied the possibility of SS addition as the raw meal for Portland cement clinker production. Compared to ordinary raw materials, the use of SS did not significantly impact the mineralogical characteristics of the Portland cement clinker. In other words, SS did not affect the quality of the produced cement. It is thus concluded that SS can be utilized as a raw material in the cement manufacturing industry. Huang and Lin (2010) reported the outcome of creating cementitious materials through the use of phosphogypsum, steel slag, granulated blast-furnace slag, and limestone. The mixture containing 45% phosphogypsum, 10% steel slag, 35% granulated blast-furnace slag, and 10% limestone showed a compressive strength exceeding 40 MPa at 28 days. The primary products of hydration observed were ettringite and C-S-H gel.

SS was also proven as an aggregate in high-strength and refractory concrete (Brand & Roesler, 2015; Ivana, Sanja, & Tatjana 2014; Maslehuddin, Sharif, Shameem, Ibrahim, & Barry, 2003; Netinger, Kesegic, & Guljas, 2011; Papayianni & Anastasiou, 2010; Qasrawi, 2014; Qasrawi, Shalabi, & Asi, 2009; Sharba, 2019; Tsakiridis et al., 2008; Wang, Yan, Yang, & Zhang, 2013). Qasrawi et al. (2009) reported that the concrete with fine SS aggregate showed the higher UCS from 1.1 to 1.3 times of traditional concrete. Netinger et al. (2011) indicated that the fire resistance of SS concrete and the river aggregate mix was similar up to 400°C, and fire resistance was significantly improved at high-temperature ranges. Ivana et al. (2014) demonstrated that when cement was present in low amounts, the strength of SS-gravel concrete mixes rose as the amount of SS content increased. Maslehuddin et al. (2003) conducted a study to compare the properties of SS and crushed limestone aggregate concretes. From the results, the authors reported that SS aggregates have the higher bulk specific gravity compared to crushed limestone aggregates, leading to the higher unit weight of SS cement concretes compared to those of crushed limestone cement concretes. However, SS cement concretes exhibited a better than crushed limestone cement concrete in not only durability characteristics but also some physical properties.

SS aggregate can be utilized for both surface layers and unbound bases/subbases in pavement applications, particularly in asphaltic surface layers because of its superior qualities such as high strength, strong binder adhesion, and high resistance to friction and abrasion (Motz & Geiseler, 2001). With the excellent stability, hardness, and bonding characteristics of SS aggregate, it may be possible to use thinner SS asphalt layers in certain circumstances. The angular shape of the SS aggregate particles promotes a tighter interlocking between them, resulting in increased resistance of SS asphalt to wheel track formations (Qasrawi, 2014). Kehagia (2009) made a skidding resistance study of asphalt wearing courses that included SS aggregates. The results indicated that SS asphalt concretes outperformed NA asphalt concretes in terms of skid resistance after one year. The strong bond formation properties of SS with bitumen make it possible to create high peeling resistance asphalts. Additionally, the high strength and close interlocking of SS particles enhance the permanent deformation resistance of asphalt under high-temperature conditions (Zalnezhad & Hesami, 2020). Hasita et al. (2020) examined the possibility of using SS or granite (G) instead of natural limestone (L) in asphalt concrete at different aggregate particle sizes (Bin 1: <4.75 mm, Bin 2: <12.50 mm, Bin 3: <19.0 mm, and Bin 4: <25.0 mm). The findings revealed that Marshall stability properties of the asphalt concrete improved when SS was used to replace limestone by up to 50%. Furthermore, the asphalt mixes with SS replacements exhibited greater fatigue life and resilient modulus, lower rut depth in comparison to the limestone mixes (Figure 2.2, 2.3). Consequently, the SS mixes were deemed to have a longer service life with the same thickness.

A comprehensive study was performed by Aiban in order to determine the characteristics of SS and its potential in road bases applications in Eastern Saudi Arabia (Aiban, 2006). The results indicated that SS with the carefully selected gradation provided the CBR values of base courses that were more than twice those for base courses using conventional Eastern Saudi calcareous aggregate. SS can also be used to improve the strength of locally available materials such as sand and marl and minimize the transporting cost of materials. The maximum limit addition of marl to SS is 60% which is dependent on the plasticity and quality of marl. The high

CBR values were obtained at the maximum addition of 60% Abu Hadriyah marl, the higher the SS content the higher the CBR.

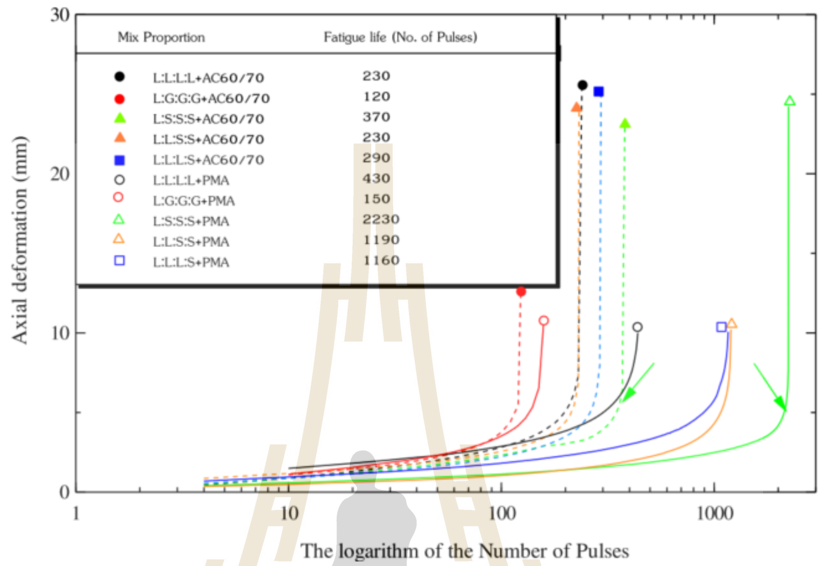


Figure 2.2. Fatigue life of mixes with different proportions of aggregates (Hasita et al., 2020).

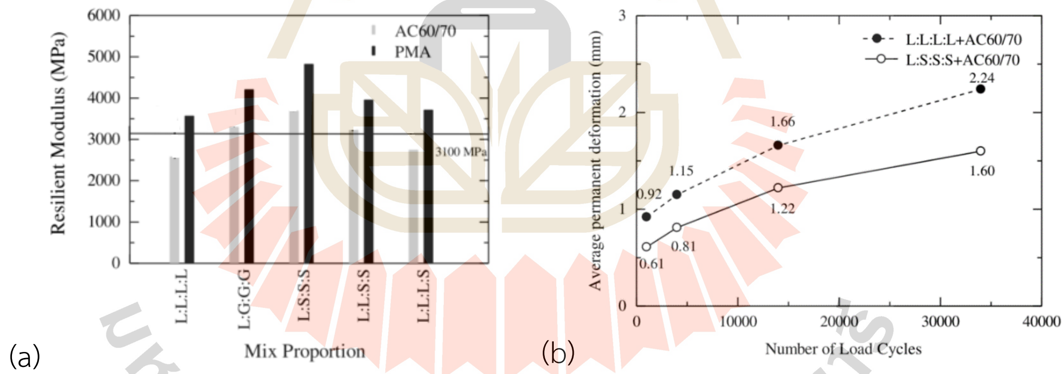
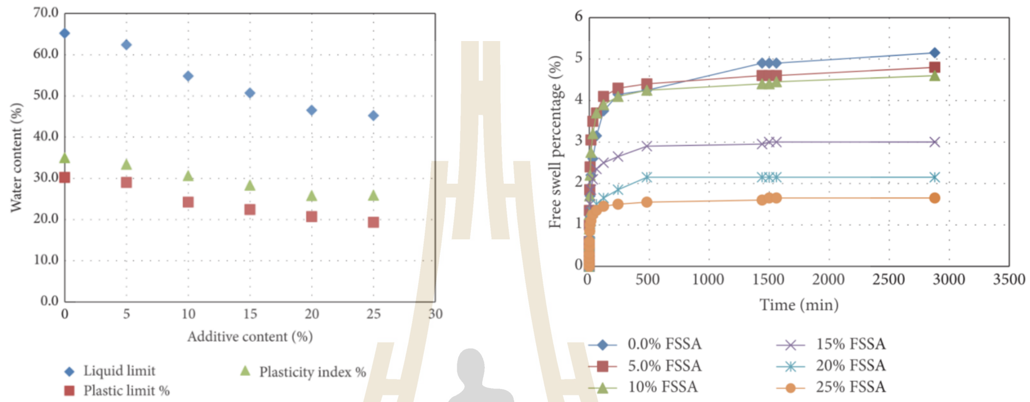


Figure 2.3. Resilient modulus (a) and permanent deformation (b) of mixes with different proportions of aggregates (Hasita et al., 2020).

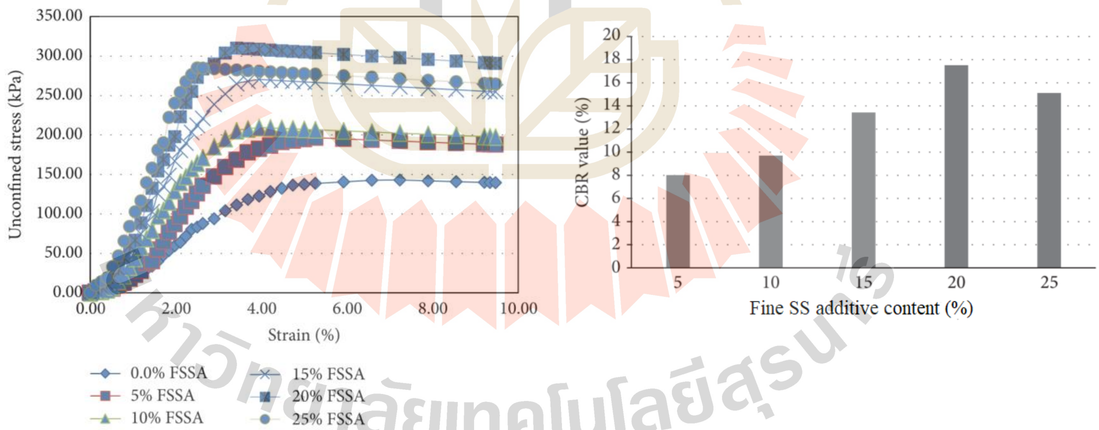
With the same research aim to reduce the negative environmental effect of SS, Aldeeky and Hattamleh (2017) obtained a positive result in studying the use of fine SS aggregate to improve the geotechnical properties for high plastic subgrade soil. They observed that 20% fine SS aggregate additives reduced plasticity index and free swell by 26.3% and 58.3%, respectively (Figure 2.4). Moreover, 20% fine SS aggregate additives will increase the UCS, MDD, and CBR values by 100%, 6.9%, and

154%, respectively (Figure 2.5). The result demonstrated that utilizing fine SS aggregate as an admixture can enhance the geotechnical traits of the soil, indicating a beneficial impact. This approach can be utilized not only to improve the geotechnical features of subgrade soil but also to address the issue of waste disposal.



(a) (b)

Figure 2.4. Plasticity index (a) and free swell (b) of high plastic subgrade soil samples using additive of fine SS (Aldeeky & Hattamleh, 2017).



(a) Unconfined stress and strain for samples with different fine SS contents

(b) CBR values correspond to MDD for fine SS additive content.

Figure 2.5 (a) UCS and (b) CBR of samples with various fine SS additive contents (Aldeeky & Hattamleh, 2017).

Sudla et al. (2018) reported that Marginal lateritic soil (LS) was improved by SS replacement. SS is a coarse-grained and non-plastic material with high abrasion resistance, which can enhance the marginal LS in both physical and mechanical properties. With higher SS replacement contents, SS reduced the fines content and therefore increased the soakage CBR and decreased swelling of LS:SS blend compared to the blends with lower SS replacement contents or without SS. Replacing the original parent material with SS resulted in an enhancement of its mechanical properties, satisfying the Department of Highways' prescribed standards for an engineering fill material in Thailand. The blend with minimum SS replacement content of 10% met the requirements of physical and mechanical properties for engineering fill materials.

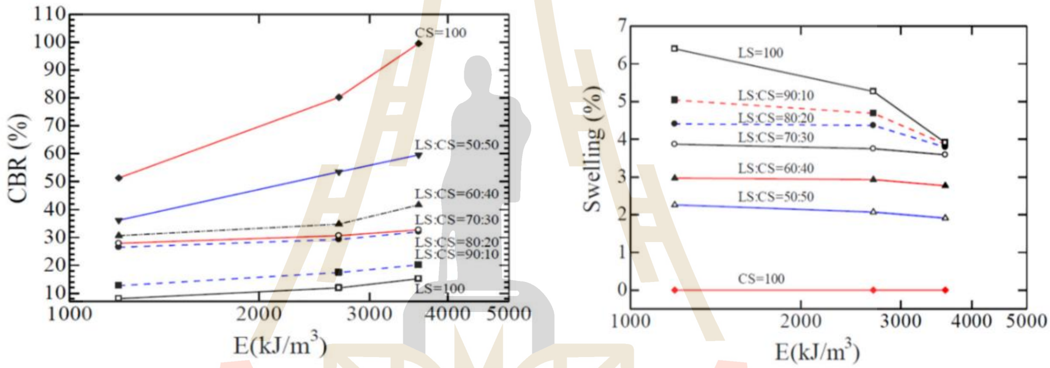


Figure 2.6 Soaked CBR and Swelling of LS:SS blends at different compaction energy (Sudla et al., 2018).

Liu, Yu, and Wang (2020) examined the possibility of SS application in the pavement base layer and determined the optimum replacement content of aggregate. The results of the experiment indicated that using SS in concrete reinforcement has benefits in strength and shrinkage performances, making it possible to use SS as a substitute for natural aggregate. The optimum replacement content was found at 50% of SS providing the maximum strength and stiffness, and the minimum mass losses. As the amount of SS increased, the temperature shrinkage performance decreased while the freeze resistance and dry shrinkage performance improved. These improvements were due to the increase of hydration products, electrostatic interaction, and bonding effect with cement when SS was added, leading to a tighter structure and lower porosity, which was confirmed by the microstructure analysis.

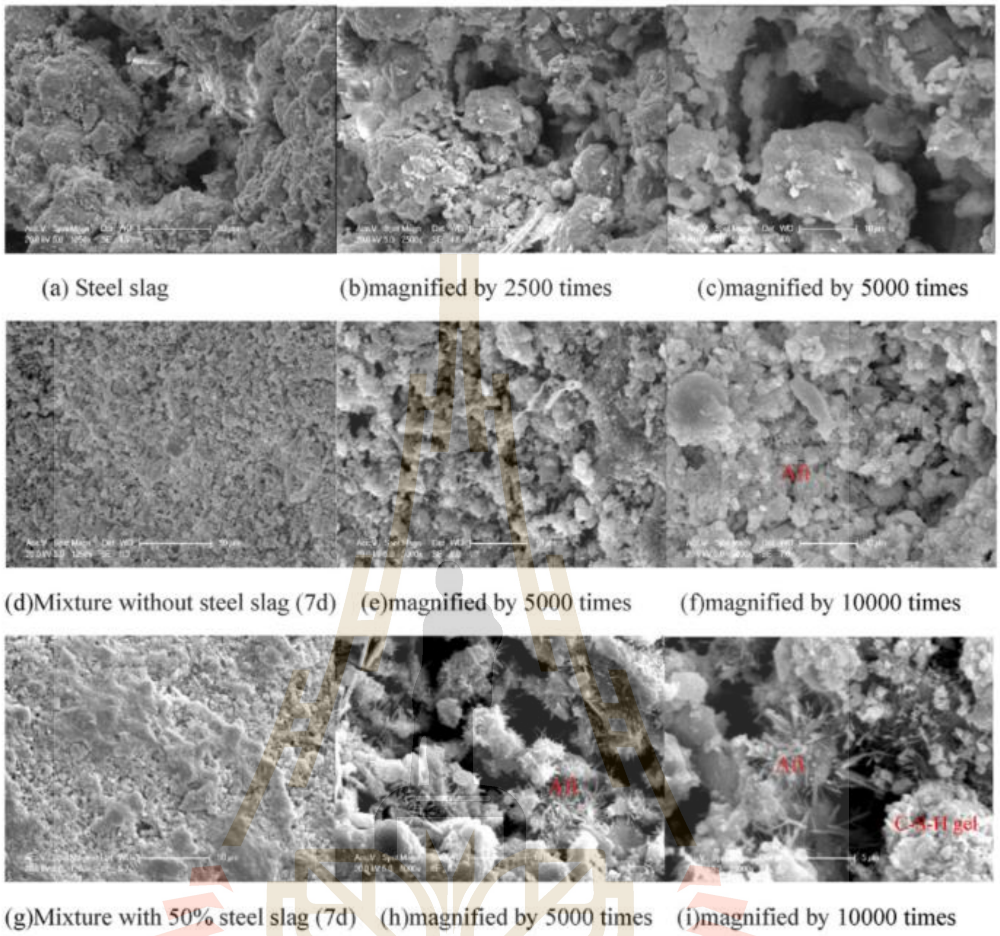


Figure 2.7 SEM images show the amount of hydration product in samples with/without SS (Liu et al., 2020).

2.2.2 Recycled concrete aggregate (RCA)

Similar to steel slag, a large amount of recycled concrete aggregate (RCA) is generated during the construction, reconstruction, expansion, or demolition of buildings, roads, and bridges. In new structures, RCA may perform differently than natural aggregates (NA) because of their differing properties.

a. Density, Porosity, and Water Absorption

The density, porosity, and water absorption of RCA are mainly affected by the residual adhered mortar on aggregates. The density of RCA is generally lower than NA density. According to research conducted by Limbachiya, Leelawat, and Dhir (2000), the relative density of RCA in a saturated surface dry state is approximately

7-9% lower than that of NA. In a similar study, Sagoe-Crentsil, Brown, and Taylor (2001) reported a density difference of 17% between SS and NA, with bulk densities of 2.394 kg/m^3 and 2.890 kg/m^3 for RCA and NA, respectively. NA has higher density and lower water absorption than RCA because RCA has high porosity and sometimes contains much more contaminants (Agrela et al., 2012). The lower density of RCA is caused by the adhered mortar that is light-weight compared to NA in the same volume.

Porosity and water absorption are typical RCA characteristics. The high porosity allows RCA to hold more water than NA, leading to higher water absorption. When exposed to fully saturated surface conditions, RCA was observed to have a water absorption rate of 4-4.7%, while NA only absorbed 0.5-1% of water (Shayan & Xu, 2003). Sagoe-Crentsil et al. (2001) reported water absorption value was 5.6% for RCA and 1.0% for NA. 4.9 - 5.2% and 2.5% for RCA and NA absorptions, respectively were found by Limbachiya et al. (2000).

b. Shape and gradation

The shape and gradation of RCA are affected by the RCA producing method and crusher type used. The aggregate particle shape influences the workability of the structure. RCA shape is generally more angular than NA. Gradation of RCA must lie in the range within the gradation requirement for each structure type that is accepted by the engineering international or local authorities.

c. Crushing and Los Angeles abrasion

Crushing and Los Angeles (LA) abrasion tests are used to evaluate the durability of materials. The LA abrasion test results indicate that RCA has more fine particles than NA when crushed or exposed to the impact of steel balls, which shows that RCA is lower durable than NA. This is because the residual mortar in RCA can be easily removed when subjected to loading, whereas NA does not have a similar coating to lose, hence leading to the higher LA abrasion value of RCA. Crushing tests showed values of 23.1% for RCA and 15.7% for basalt (Sagoe-Crentsil et al., 2001), 24% for RCA, and 13% for basalt (Shayan & Xu, 2003). LA abrasion values for RCA and NA were found as 32% and 11%, respectively (Shayan & Xu, 2003), and 26.4 - 42.7% and 22.9%, respectively (Tavakoli & Soroushian, 1996). The weakness of the adhered mortar was revealed by the crushing and abrasion tests. Since this layer is most likely broken off and separated from the aggregate, probably, this mortar layer may also create a weak bond in concrete.

d. RCA in pavement applications

RCA has shown a high potential in recycling and reuse. In recent decades, numerous studies have been carried out to assess the practicality of using RCA materials in projects involving concrete, mortar, and road construction (Cardoso, Silva, Brito, & Dhir, 2016; Hou, Ji, Su, Zhang, & Liu, 2014; Jones, Zheng, Yerramala, & Rao, 2012; Mills-Beale & You, 2010) (Agrela et al., 2012; Arulrajah, Piratheepan, Ali, & Bo, 2012; Ebrahim Abu El-Maaty Behiry, 2013; Kianimehr, Shourijeh, Binesh, Mohammadinia, & Arulrajah, 2019; Q. Li & Hu, 2020; Maghool, Arulrajah, Ghorbani, & Horpibulsuk, 2022; Pourkhorshidi, Sangiorgi, Torreggiani, & Tassinari, 2020; Tataranni et al., 2018).

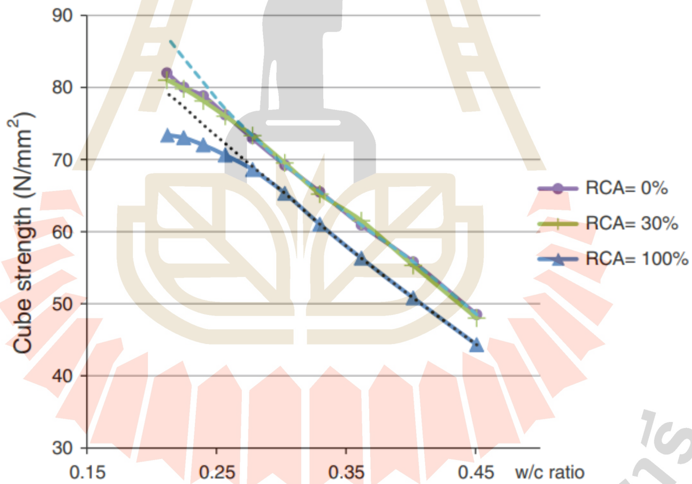


Figure 2.8 Concrete compressive strength at different water-to-cement (w/c) ratios and different RCA contents (Limbachiya et al., 2000).

With the difference between RCA and NA properties, they behave differently in the concrete mix and the RCA finished concrete performs unlike NA (conventional) concrete. The compression strength of RCA concrete is affected by several factors including w/c ratio, properties and percentage of RCA in the mix, and the amount of adhered mortar on the RCA. In a research by Limbachiya et al. (2000), with the same w/c ratio, compressive strength of concrete mixes was found the same at 0% and 30% of RCA replacements while concrete mix with 100% of RCA showed lower compressive strength Figure 2.8. Etxeberria, Vázquez, Marí, and Barra (2007) also reported that up to 25% of RCA can be replaced without significant change in compression strength. However, the w/c ratio needs to be 4 - 10% lower to obtain the similar strength at 50 - 100% RCA, otherwise, the compression strength of concrete mix with 100% RCA was reduced by 20 - 25%.

Several studies have found that the addition of RCA material has less effect on the splitting tensile strength of concrete mix than its compressive strength. Kang, Kim, Kwak, and Hong (2012) reported that RCA concrete displays comparable splitting tensile strength to NA concrete and, in some cases, even exhibits superior tension performance. Tavakoli and Soroushian (1996) reported that under different conditions such as aggregate size, water-to-cement ratio, and dry mix time, most RCA concrete samples demonstrated higher tensile strength than NA concrete samples (Figure 2.9). The percentage of elastic modulus decrease is different in various studies when RCA is used (Froudinstou-Yannas, 1977; Maruyama, Sogo, Sogabe, Sato, & Kawai, 2004).

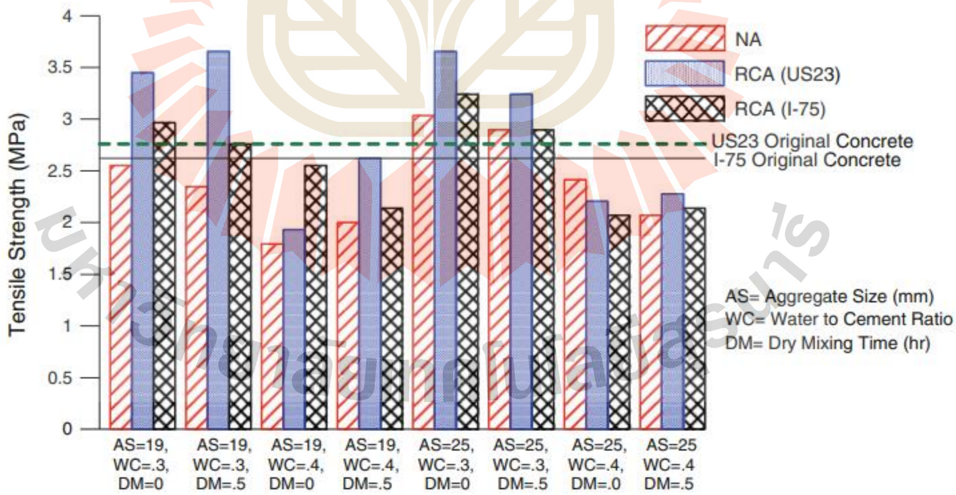


Figure 2.9 Splitting tensile strength of RCA and NA concretes with varied conditions of aggregate size, w/c ratio, and dry mix time (Tavakoli & Soroushian, 1996)

The shrinkage of concrete occurs during the drying process of concrete, which is influenced by factors such as the amount of binder, the water-to-cement ratio, and the type of aggregate used. When using recycled concrete aggregate (RCA), the level of shrinkage of concrete increases proportionally with the increase of RCA replacement (Yang, Chung, & Ashour, 2008). Because RCA concrete contains more binder (old and new), it has a higher shrinkage level (20-50% more) than natural aggregate (NA) concrete (Corinaldesi, 2010). When NA is totally replaced by RCA, the shrinkage of concrete increases by approximately 80% compared to NA concrete. Most researchers agree that shrinkage deformation of RAC prepared with fine RCA is greater than coarse RCA (Etxeberria et al., 2007).

RCA is also used in cement stabilization by several researchers (Chakravarthi, Boyina, Singh, & Shankar, 2019; Q. Li & Hu, 2020; Yaowarat et al., 2020). In cement stabilized RCA and conventional aggregates (VA), Chakravarthi et al. (2019) found a significant development in the strength of cement stabilized RCA and VA blends compared to cement stabilized RCA at all cement content. The maximum strength was recognized at RCA:VA ratio of 50:50. When compared to the cement stabilized reclaimed asphalt pavement (RAP), cement stabilized RCA provided remarkably higher strength at the same cement content (Figure 2.10).

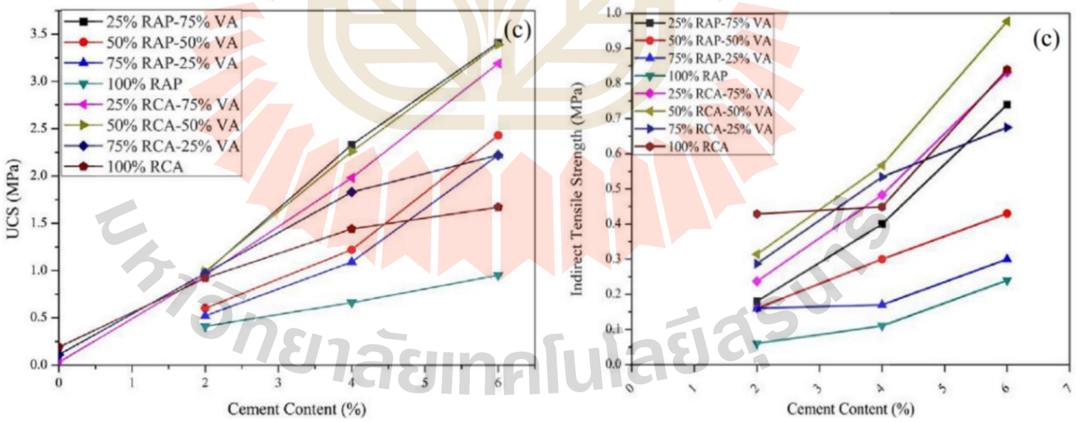


Figure 2.10 7-day cured UCS and ITS of cement stabilized RCA:VA and RAP:VA blends at different cement content (Chakravarthi et al., 2019).

However, cement stabilized RCA required a high cement content (>5%) to achieve the specifications of the base layer for high-volume roads. The authors also reported that the maximum elastic modulus was recorded at RCA:VA ratio of 25:75 and cement content of 6%. Whereas, the elastic modulus tremendously decreased for blends of 100% RCA and 75% RCA-25% VA at 6% cement content because of the high brittle of material due to the high cement content and high existing residual mortar surrounding the aggregates (Figure 2.11).

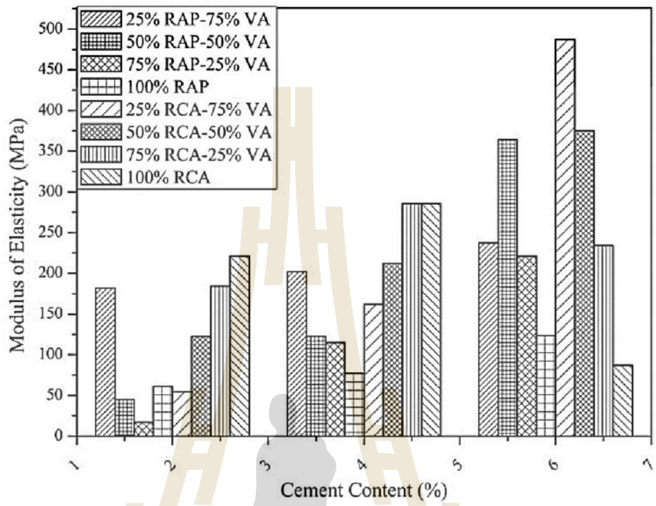


Figure 2.11 The elastic modulus of cement stabilized RCA:VA and RAP:VA blends at different cement content (Chakravarthi et al., 2019)

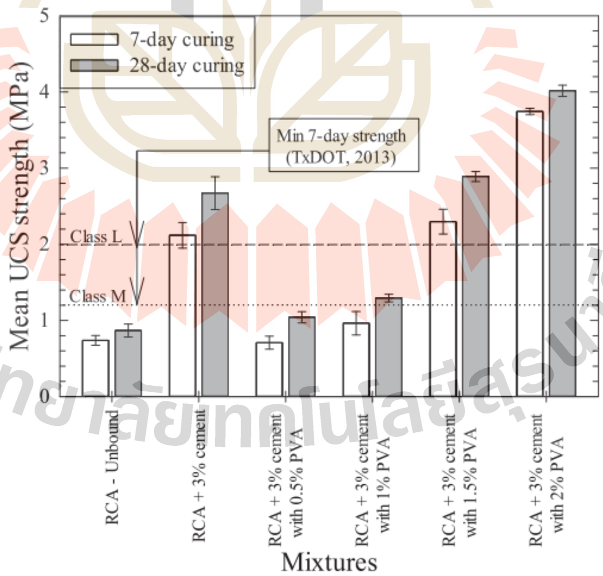


Figure 2.12 UCS values of cement stabilized RCA and cement-PVA stabilized RCA at 7-day and 28-day cured times (Yaowarat et al., 2020)

Yaowarat et al. (2020) studied on the potential of RCA as the pavement base/subbase material. Cement and polyvinyl alcohol (PVA) were used as additives to improve the mechanical strengths of RCA. With the proper dosages of cement (3%) and PVA (1.5% or 2%), the results indicated that 7-day cured UCS of both cement-stabilized RCA and cement-PVA stabilized RCA achieved the minimum requirement of road construction authorities (Figure 2.12). In addition, the resilient modulus values for both types of stabilized RCA exceeded the minimum recommended value, and an increase in resilient modulus over time was also observed.

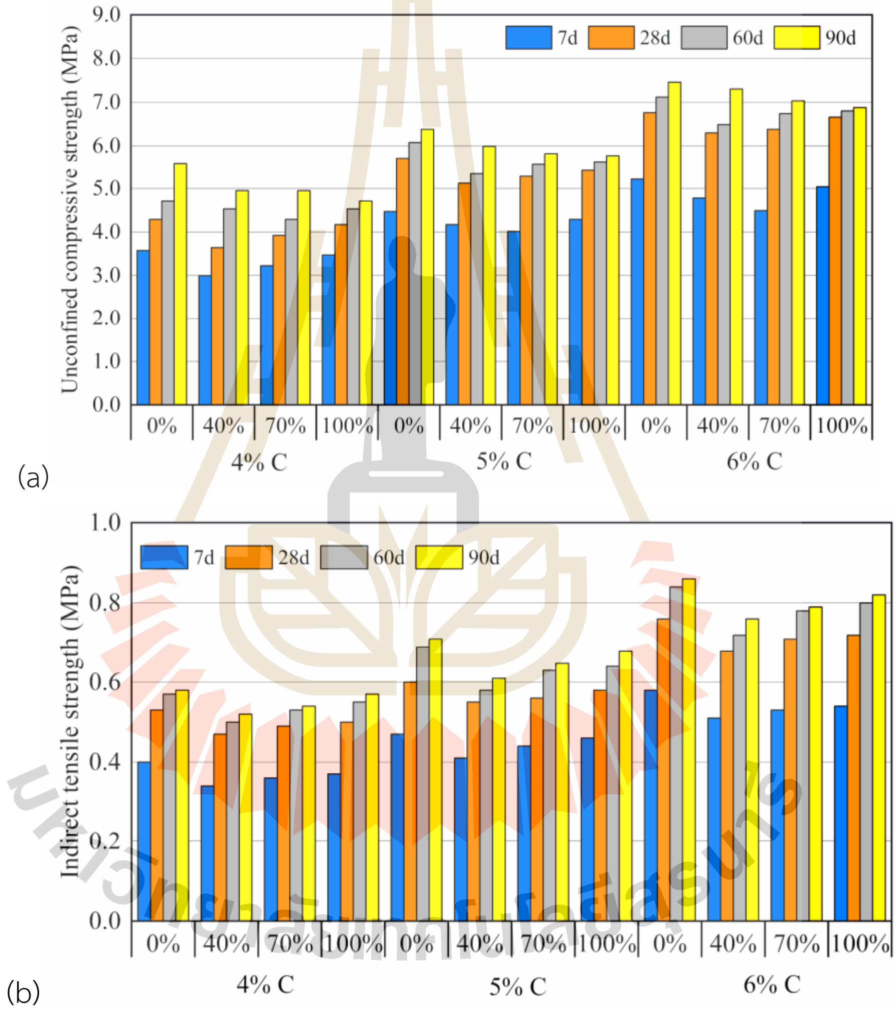


Figure 2.13 UCS (a) and ITS (b) of cement stabilized RCA:NA with different RCA replacements at different cured times (Q. Li & Hu, 2020).

Q. Li and Hu (2020) researched the use of RCA in the partial replacement of NA in cement stabilized materials. The results indicated that though the RCA replacements led to a decrease of strength compared to the cement stabilized NA, the 7-day strength of cement stabilized RCA:NA blends met the minimum requirement for road bases (Figure 2.13). The cement stabilized RCA:NA with high RCA replacement showed an obvious reduction of dry shrinkage (Figure 2.14).

Kianimehr et al. (2019) evaluated the viability of using RCA in the improvement of the shear/compressive strengths and deformation properties of clay soils. The findings demonstrated that incorporating RCA into clay soils resulted in lower density and greater unconfined compressive strength (UCS) with the increase of moist curing. In comparison to pure clay soil, RCA and Clay soil blends exhibited higher tendencies for dilative behavior during shear and higher shear strengths. It is concluded that adding RCA in clay soils leads to stronger, stiffer, and less compressible blends which are particularly suitable for pavement construction purposes of base/subbase/subgrade.

It has been found that RCA lacks different properties than NA due to which the performance of structure containing RCA (qualitative uncertainty and variability) is inferior to structure containing NA. Though RCA expresses some disadvantages compared to natural materials, it still satisfies the requirements of construction authorities. Therefore, RCA has been used as a potential material supporting sustainable development in the construction industry. Researching sustainably RCA has become an essential part of sustainable development and continues to play an important role in the future.

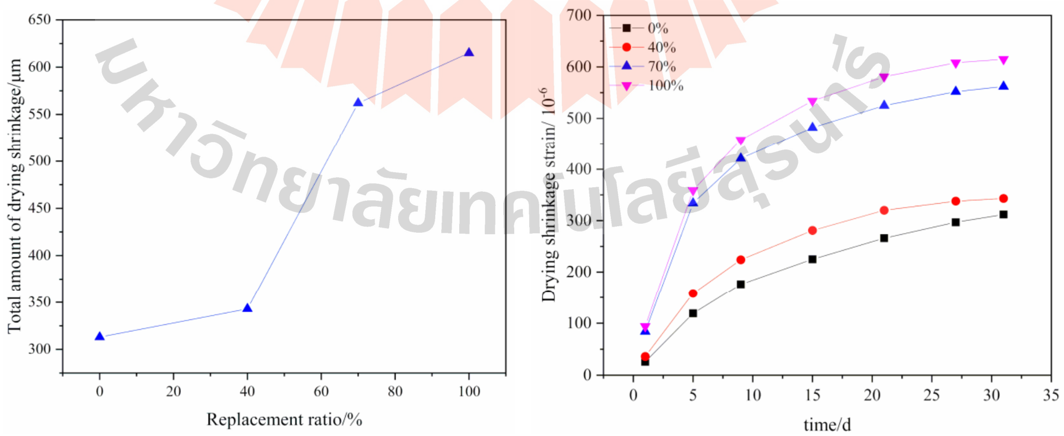


Figure 2.14 Total amount of drying shrinkage and the dry shrinkage development with time cement stabilized RCA:NA with different RCA replacements (Q. Li & Hu, 2020).

The results obtained in this literature survey agree to conclude that recycled aggregates such as SS and RCA are possibly used as construction materials in pavement applications with quality comparable to those produced with NA. In conclusion, the use of recycled materials as construction materials for pavement is technically feasible, economical, and constitutes an eco-friendly approach for future industrial waste management strategies.

2.3 Natural rubber latex in pavement applications

Natural rubber latex (NRL) is a natural polymer whose application in construction has become a new trend that has been extendedly encouraged because it is an effective and environmentally-friendly additive alternative to synthetic polymers. Indeed, NRL has been researched and proven its effectiveness in compressive, tensile, and flexural strengths improvement of cement mortar, cement paste, concrete technology, and cement-stabilized soils (Buritatun et al., 2020; Jose & Kasthurba, 2020; Muhammad, Ismail, Bhutta, & Abdul-Majid, 2012; Sukmak et al., 2020; Vo & Plank, 2018; Yaowarat et al., 2021).

Yaowarat et al. (2021) reported that the pores of NRL-concrete specimens were infiltrated by the NRL films. At the optimum rubber/cement (r/c) ratio of 1.16%, the films in concrete matrixes were thin which linked and reinforced cement matrixes and hence improved flexural strength. At the higher r/c ratio, however, the thicker NRL films retarded the hydration and hardening processes of cementitious products and led to the lower compressive and flexural strengths of concrete.

The addition of NRL was proved to improve the flexural and toughness of cement paste while retarding the setting time and hydration. The maximum flexural strength was found at the optimum r/c ratio. Beyond this optimum, the flexural strength decreased but with higher flexural deflection (Sukmak et al., 2020). A similar finding was found in NRL application in cement stabilized lateritic soil (Buritatun et al., 2020).

Jose and Kasthurba (2020) studied the effect of NRL on the properties of laterite soil-cement blocks and reported that the rubber particles were observed filling inside the pores and holding the soil particles, which decreased the total pore volume and therefore reduced the water absorption. The minimum number of pores was found at the optimum NRL of 3%. However, for the larger NRL contents, the excess NRL particles reduced the soil cohesion. The replacement of cement particles by rubber particles may be the reason for the reduction in cohesion and thus reduced compressive strength. In addition, the growth of 33% in weathering resistance property and the weight loss less than 1.25% of laterite soil-cement block were observed at 2% of NRL. The results of this research also concluded that the thermal conductivity of laterite soil-cement blocks was decreased by 3.5% with the addition of 1% of NRL. Thus, the NRL application is positive in tropical climate countries by offering higher thermal insulation.

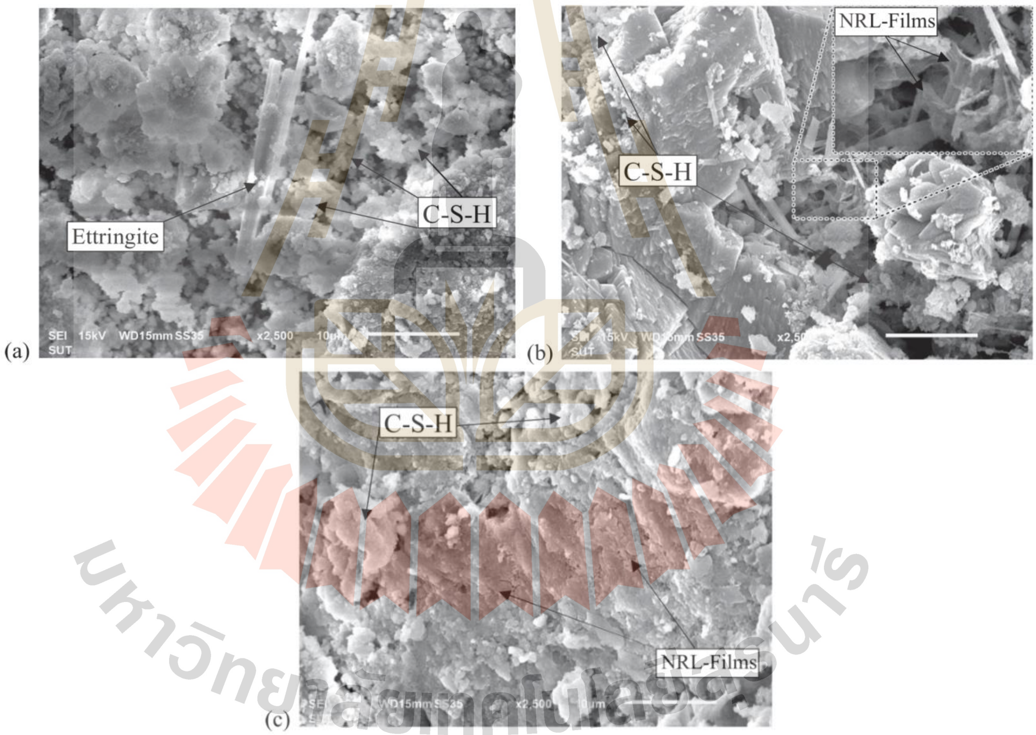


Figure 2.15 The microstructure of NRL-concrete for w/c = 0.4 at (a) r/c = 0; (b) r/c = 1.16 (optimal); (c) r/c = 5.78 (Yaowarat et al., 2021).

Though the NRL has shown its effectiveness as an additive that can improve the properties of structures in pavement application, the study on cement-natural rubber latex stabilized recycled aggregates is in its infancy while the recycled aggregates are considered eco-friendly and cost-effective materials with the increasing application demand. Thailand is one of the large producers of natural rubber latex worldwide. Besides exporting, the Thailand government has also encouraged research and applications of NRL in construction, especially, in pavement applications as the road transportation system in Thailand has been rapidly growing.

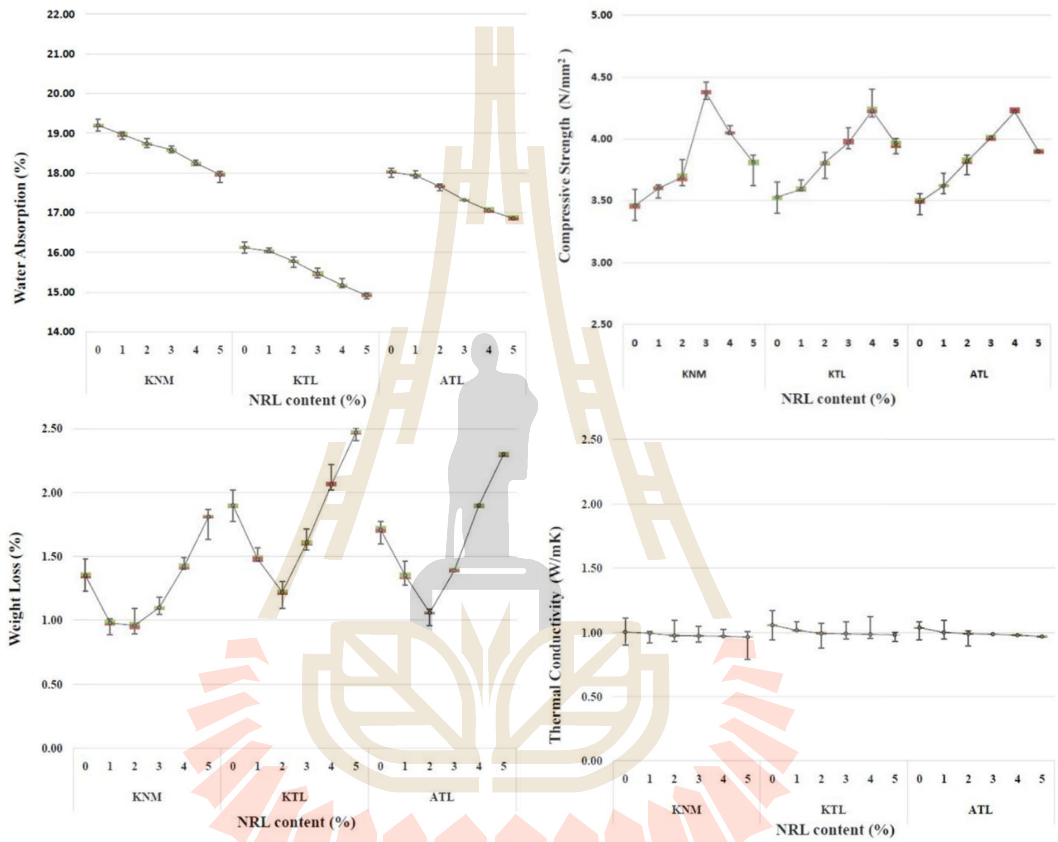


Figure 2.16 Variation of water absorption, compressive strength, weight loss, and thermal conductivity of laterite soil-cement blocks corresponding NRL contents (Jose & Kasthurba, 2020).

2.4 Properties of cement stabilized materials and related pavement performance

Using cement stabilized materials (CSM) as backfill materials for road base/subbase or subgrade is a beneficial choice to control the project cost compared to the asphalt mixture. The granular unbound structural layer is transformed into the stabilized structural layer by the stabilization of cementitious materials. This significantly increases the tensile strength and improves the bearing capacity of the stabilized layer. In order to increase the serviceability of pavement during the design service life, it is necessary to enhance the durability of CSM. The deterioration of the CSM structure layer is closely linked to factors such as material composition, traffic load, and environmental impact. The shrinkage crack development, erosion of fine materials due to environmental effects, deformation, and fatigue failure under traffic load are considered the main reasons causing the failure of the CSM layer. The failure mechanism and durability improvement measures of CSM under different factors are important aspects that are necessary to be evaluated for sustainable development.

2.4.1 Strength and modulus of cement stabilized layers and related pavement performance

The strength of the cement stabilized layer (CSL) is crucial because it directly controls the performance of CSL and thus affects the overall pavement performance. Furthermore, various measures of CSM strength are used to determine its specific engineering behavior. The modulus of rupture is a significant factor in the fatigue failure of CSL. Tensile strength plays an important role in the development of shrinkage cracking in CSL. The unconfined compressive strength (UCS) is a critical parameter for the top compression fatigue model and is often used in mix design tests. In Thailand, UCS is used as a conference value to control the quality of mix designs for pavement base structures. Thailand Department of Highway (DH-S204/2556, 2013) specifies the minimum 7-day UCS values of soil cement base are 1.724 MPa for low traffic volume roads and 2.413 MPa for high traffic volume roads. The UCS has a well-established correlation with ITS and resilient modulus for cost-effective and time-saving in geotechnical and pavement engineering design (Chhorn, Hong, & Lee, 2018; Din & Rafiq, 1997; Nazir, Momeni, JahedArmaghani, & Amin, 2013; Rashidi, Ashtiani, Si, Izzo, & McDaniel, 2018).

Theyse, De Beer, and Rust (1996) reported that the development of UCS can mitigate the compression fatigue and the increase of breaking strain lead to tension fatigue decrease. The yield strength of damaged CSL is negatively related to the plastic strain of CSL. Thompson (1986) showed the increase of MOR reducing fatigue cracking. George George (2001) reported that a low strength or low modulus/strength ratio is positive in mitigating shrinkage cracking.

The strength of CSM is influenced by several factors. The tensile strength of cement stabilized soil is affected by molding water content, aggregates (type, gradation, shape), curing conditions, compaction efforts, compaction type, and cement content (Jayawickrama et al. 1998). The strength reduction of CSM can occur due to the delayed compaction and the high UCS values can be obtained with high levels of compaction effort. The increase in water content reduced the UCS value (Buritatun et al., 2020). In contrast, the increase in cement content develops the UCS and resilient modulus values (Arora & Aydilek, 2005; Buritatun et al., 2021; Buritatun et al., 2020). Resilient modulus and UCS of lightly stabilized soil are also enhanced by the 30% increase of fines content (Ashtiani, Little, & Masad, 2007). The ITS values of CSM were highest at molding optimum liquid content (1.0 OLC) and lower at 0.8 OLC and 1.2 OLC of molding liquid content (Buritatun et al., 2021).

2.4.2 Shrinkage of cement stabilized materials and related pavement distress

The bonding between the surface layer and the cement stabilized base layer is closely related to the cracking of the surface layer which might be caused by the shrinkage cracking of cement stabilized layers (CSL). Shrinkage in the cement-stabilized layer is caused by the reduction in volume due to cement hydration, moisture loss, and temperature decrease. George (1990) reported that the bonding from the underlying layer restrains the shrinkage of the cement-stabilized layer, which causes the development of tensile stress in the surface layer. This leads to occurring shrinkage cracking when the tensile stress develops exceed the tensile strength of the stabilized materials. Shrinkage of CSL is affected by material characteristics, moisture content, additive content, and curing conditions. George (1990) reported that the higher moisture content compared to the OWC causes excessive shrinkage cracking. Hence, the reduction of shrinkage can be obtained by decreasing molding water content, increasing compaction density, avoiding montmorillonite clay, and controlling the degree of saturation to 70%.

In the early stage of CSM base design, the high cement content in the mixture is normally required to achieve high mechanical strength, which increases the stiffness but decreases the toughness of the CSM base layer. It is prone to tensile and shrinkage cracks at the bottom of the structure layer. Liao, Chen, Jiang, and Lei (2012) made a comparison in the mechanical properties and crack resistance of CSM at various cement content. Results showed that the mechanical properties of CSM displayed an increasing trend corresponding to the increase of cement content and the dry-shrinkage strain was minimized at optimum cement content of 3.5%.

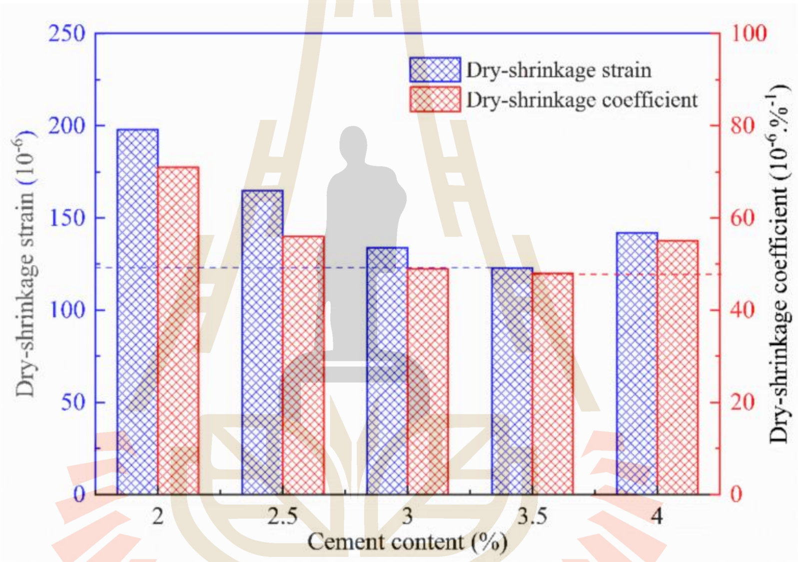


Figure 2.17 Dry-shrinkage strain and Dry-shrinkage coefficient of CSM (Liao et al., 2012).

2.4.3 Fatigue of Cement stabilized layer related to pavement distress

Fatigue occurs in the pavement as a result of repeated loads caused by traffic. The reduction in fatigue resistance of CSM can be caused by decreasing modulus value, decreasing density, increasing moisture content, or insufficient mixing. The fatigue life of CSL typically is related to the stress or the strain ratio (Jitsangiam, Nusit, Chummuneerat, Chindaprasirt, & Pichayapan, 2016; Yu, Wei, & Ma, 2011). The number of cycles to 50% of the initial modulus value is considered to be the fatigue life of CSM in the beam tests (Midgley & Yeo, 2008).

Bottom-up tensile fatigue in CSL occurs as a result of tensile strain at the bottom of the CSL due to the repeated traffic loads (Y. Li, Metcalf, Romanoschi, &

Rasoulian, 1999; Pretorius & Monismith, 1972). Under these loads, tensile stress/strain initiated the microcracks at the bottom of the CSL and thereby spread upwards. The fatigue of the CSL caused a reduction in its modulus values, which increased the tensile strain at the bottom of the layer, resulting in fatigue cracking in the surface layer. When CSL experiences freeze-thaw and/or wet-dry cycles, the strength and modulus value decrease, which reduces its fatigue resistance (Naji & Zaman, 2005). Sountharajah, Bui, Nguyen, Jitsangiam, and Kodikara (2018) reported that the pavement fatigue damage increased when the CSL layer thickness decreased. The fatigue of CSL is directly related to the strength of the cement stabilized materials. The IDT strength increase of cement stabilized materials increases fatigue resistance (Hadley, Hudson, & Kennedy, 1972). The increase in break strain of cement stabilized materials increases the tensile fatigue life of CSL (Theyse et al., 1996).

For a thick CSL, the repeated compression at the top of CSL may cause fatigue failure, compression/crushing fatigue in the CSL, and result in rutting of pavement. The tensile strain at the bottom of the CSL is insufficient to induce tensile fatigue in these layers. However, the high compressive strain cause crushing in the top 2-3 inches, particularly when there is excessive moisture presence (De Beer, 1990). An increase in the UCS of CSM decreases the compression strain and improves the crushing fatigue life (Theyse et al., 1996). A compressive strain of 1% has believed to be the failure strain for compression fatigue. Top-down compressive fatigue typically occurs when a thin asphalt layer is placed on top of a lightly stabilized thick layer.

2.4.4 Wetting-Drying durability of CSL

In cement stabilized layer, the deterioration occurs as a result of environmental impact such as wetting and drying (w-d) cycles. The strength and stiffness values of the CSL are reduced as the number of w-d cycles increases, which might affect the fatigue cracking resistance (Buritatun et al., 2021; Hoy, Rachan, Horpibulsuk, Arulrajah, & Mirzababaei, 2017; Paige-Green & Ware, 2011). Wen and Ramme (2008) investigated a field study and they found a significant reduction of the UCS at the middle of the traffic lane of CSL, the strength is less than 10% compared to the original UCS after seven years of service. The strength loss in the middle area of the road lane suggests that the decline in the strength of the CSL material was mainly due to environmental factors rather than traffic-related conditions. Furthermore, the decrease in stiffness and strength creates significant surface deflections and high-stress levels in the surface layer, which results in bottom-up fatigue cracking in the surface layer.

In summary, wetting and drying durability is necessary to be considered in pavement design and analysis because of its significant influence on the performance of CSL.

2.5 References

Agrela, F., Barbudo, A., Ramírez, A., Ayuso, J., Carvajal, M. D., & Jiménez, J. R. (2012). Construction of road sections using mixed recycled aggregates treated with cement in Malaga, Spain. *Resources, Conservation and Recycling, 58*, 98-106. Doi: 10.1016/j.resconrec.2011.11.003

Aiban, S. A. (2006). Utilization of steel slag aggregate for road bases. *Journal of Testing and Evaluation, 34*(1).

Aldeeky, H., & Hattamleh, O. A. (2017). Experimental Study on the Utilization of Fine Steel Slag on Stabilizing High Plastic Subgrade Soil. *Advances in Civil Engineering, 2017*, 1-11. Doi: 10.1155/2017/9230279

Alizadeh, R., Chini, M., Ghods, P., Hoseini, M., Montazer, S., & Shekarchi, M. (2003). Utilization of Electric Arc Furnace Slag as Aggregates in concrete - Environmental issue. *6th CANMET/ACI International Conference on Recent Advances in Concrete Technology, Bucharest, Romani*, 451-464.

Altun, I. A., & Yılmaz, I. (2002). Study on steel furnace slags with high MgO as additive in Portland cement. *Cement and Concrete Research, 32*, 1247–1249.

Andreas, L., Herrmann, I., Lidstrom-Larsson, M., & Lagerkvist, A. (2005). Physical properties of steel slag to be reused in a landfill cover. Sardinia 2005. *Tenth Int. Waste Management and Landfill Symp., S. Margherita di Pula, Cagliari, Italy*.

Arora, S., & Aydilek, A. H. (2005). Class F Fly-Ash-Amended Soils as Highway Base Materials. *Journal of Materials in Civil Engineering, 17*, 640-649. Doi: 10.1061/(ASCE)0899-1561(2005)17:6(640)

Arulrajah, A., Piratheepan, J., Ali, M. M. Y., & Bo, M. W. (2012). Geotechnical Properties of Recycled Concrete Aggregate in Pavement Sub-Base Applications. *Geotechnical Testing Journal, 35*(5). Doi: 10.1520/gtj103402

Ashtiani, R. S., Little, D. N., & Masad, E. (2007). Evaluation of the Impact of Fines on the Performance of Lightly Cement-Stabilized Aggregate Systems. *Transportation Research Record: Journal of the Transportation Research Board, 2026*(1), 81-88. Doi: 10.3141/2026-10

Barra, M., Ramonich, E., & Munoz, M. (2001). STABILIZATION OF SOILS WITH STEEL SLAG AND CEMENT FOR APPLICATION IN RURAL AND LOW TRAFFIC ROADS. *Beneficial Use of Recycled Materials in Transportation Applications*.

Brand, A. S., & Roesler, J. R. (2015). Steel furnace slag aggregate expansion and hardened concrete properties. *Cement and Concrete Composites, 60*, 1-9. Doi: 10.1016/j.cemconcomp.2015.04.006

Buritatun, A., Horpibulsuk, S., Udomchai, A., Suddeepong, A., Takaikaew, T., Vichitcholchai, N., . . . Arulrajah, A. (2021). Durability improvement of cement stabilized pavement base using natural rubber latex. *Transportation Geotechnics, 28*. Doi: 10.1016/j.trgeo.2021.100518

Buritatun, A., Takaikaew, T., Horpibulsuk, S., Udomchai, A., Hoy, M., Vichitcholchai, N., & Arulrajah, A. (2020). Mechanical Strength Improvement of Cement-Stabilized Soil Using Natural Rubber Latex for Pavement Base Applications. *Materials in Civil Engineering, 32*(12). Doi: 10.1061/(ASCE)MT.1943-5533.0003471

Cardoso, R., Silva, R. V., Brito, J., & Dhir, R. (2016). Use of recycled aggregates from construction and demolition waste in geotechnical applications: A literature review. *Waste Manag, 49*, 131-145. Doi: 10.1016/j.wasman.2015.12.021

Chakravarthi, S., Boyina, A., Singh, A. K., & Shankar, S. (2019). Evaluation of cement treated reclaimed asphalt pavement and recycled concrete pavement bases. *International Journal of Pavement Research and Technology, 12*(6), 581-588. Doi: 10.1007/s42947-019-0069-1

Chaurand, P., Rose, J., Briois, V., Olivi, L., Hazemann, J. L., Proux, O., . . . Bottero, J. Y. (2007). Environmental impacts of steel slag reused in road construction: a crystallographic and molecular (XANES) approach. *J Hazard Mater, 139*(3), 537-542. Doi: 10.1016/j.jhazmat.2006.02.060

Chhorn, C., Hong, S. J., & Lee, S. W. (2018). Relationship between compressive and tensile strengths of roller-compacted concrete. *Traffic and transportation Engineering, 5*(3), 215-223. Doi: 10.1016/j.jtte.2017.09.002

Corinaldesi, V. (2010). Mechanical and elastic behaviour of concretes made of recycled-concrete coarse aggregates. *Construction and Building Materials, 24*(9), 1616-1620. Doi: 10.1016/j.conbuildmat.2010.02.031

De Beer, M. (1990). Aspects of the Design and Behaviour of Road Structures Incorporating Lightly Cementitious Layers. *Ph.D. dissertation, Faculty of Engineering, University of Pretoria, Pretoria (February).*

DH-S204/2556. (2013). Standard for highway construction (Soil Cement Base), Department of Highways, Bangkok, Thailand In.

Din, F., & Rafiq, M. (1997). Correlation Between Compressive Strength and Tensile Strength/Index Strength of Some Rocks of North-West Frontier Province (Limestone and Granite) *Geol. Bull. Univ. Peshawar, 30*, 183-190.

Ebrahim Abu El-Maaty Behiry, A. (2013). Utilization of cement treated recycled concrete aggregates as base or subbase layer in Egypt. *Ain Shams Engineering, 4*(4), 12. Doi: 10.1016/j.asej.2013.02.005

Etxeberria, M., Vázquez, E., Marí, A., & Barra, M. (2007). Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cement and Concrete Research, 37*(5), 735-742. Doi: 10.1016/j.cemconres.2007.02.002

Froudinstou-Yannas, S. (1977). Waste concrete as aggregate for new concrete. . *ACI Journal, 74*, 373–376.

Ge&eler, J. (1996). Use of steelworks salg in Europe. *Waste Management, 16*, 59-63. Doi: 10.1016/S0956-053X(96)00070-0

George, K. P. (1990). Characterization and structural design of cement-treat base. *Transportation Research Record, 1288*, 78 - 87.

George, K. P. (2001). Soil stabilization field trial: Interim report. *Interim Report No. FHWA/MS-DOT-RD-03-133, Mississippi Department of Transportation*.

Guo, X., & Shi, H. (2013). Utilization of Steel Slag Powder as a Combined Admixture with Ground Granulated Blast-Furnace Slag in Cement Based Materials. *Journal of Materials in Civil Engineering, 25*(12), 1990-1993. Doi: 10.1061/(asce)mt.1943-5533.0000760

Hadley, W. O., Hudson, W. R., & Kennedy, T. W. (1972). A Comprehensive Structural Design for Stabilized Pavement Layers. *Research Report No. 98-13, The Texas Highway Department (August).*

Hasita, S., Rachan, R., Suddeepong, A., Horpibulsuk, S., Arulrajah, A., Mohammadinia, A., & Nazir, R. (2020). Performance Improvement of Asphalt Concretes Using Steel Slag as a Replacement Material. *Journal of Materials in Civil Engineering, 32*(8). Doi: 10.1061/(asce)mt.1943-5533.0003306

Hou, Y., Ji, X., Su, X., Zhang, W., & Liu, L. (2014). Laboratory investigations of activated recycled concrete aggregate for asphalt treated base. *Construction and Building Materials, 65*, 535-542. Doi: 10.1016/j.conbuildmat.2014.04.115

Hoy, M., Rachan, R., Horpibulsuk, S., Arulrajah, A., & Mirzababaei, M. (2017). Effect of wetting–drying cycles on compressive strength and microstructure of recycled asphalt pavement – Fly ash geopolymer. *Construction and Building Materials, 144*, 624-634. Doi: 10.1016/j.conbuildmat.2017.03.243

Huang, Y., & Lin, Z. (2010). Investigation on phosphogypsum–steel slag–granulated blast-furnace slag–limestone cement. *Construction and Building Materials, 24*(7), 1296-1301. Doi: 10.1016/j.conbuildmat.2009.12.006

Ivana, B., Sanja, D., & Tatjana , R. (2014). Strength properties of steel slag stabilized mixes. *Composites, 58*, 386-391. Doi: 10.1016/j.compositesb.2013.11.002

Jitsangiam, P., Nusit, K., Chummuneerat, S., Chindaprasirt, P., & Pichayapan, P. (2016). Fatigue Assessment of Cement-Treated Base for Roads: An Examination of Beam-Fatigue Tests. *Journal of Materials in Civil Engineering, 28*(10). Doi: 10.1061/(asce)mt.1943-5533.0001601

Jones, R., Zheng, L., Yerramala, A., & Rao, K. S. (2012). Use of recycled and secondary aggregates in foamed concretes. *Magazine of Concrete Research, 64*(6), 513-525. Doi: 10.1680/macr.11.00026

Jose, A., & Kasthurba, A. K. (2020). Laterite soil-cement blocks modified using natural rubber latex: Assessment of its properties and performance. *Construction and Building Materials*. Doi: 10.1016/j.conbuildmat.2020.121991

Kang, T., Kim, W., Kwak, Y.-K., & Hong, S.-G. (2012). The choice of Recycled Concrete Aggregates for flexural members. *Proceedings of 18th international association for bridge and structural engineering congress on innovative infrastructures, Seoul, Korea.*

Kehagia, F. (2009). Skid resistance performance of asphalt wearing courses with electric arc furnace slag aggregates. *Waste Manag Res, 27*(3), 288-294. Doi: 10.1177/0734242X08092025

Kianimehr, M., Shourijeh, P. T., Binesh, S. M., Mohammadinia, A., & Arulrajah, A. (2019). Utilization of recycled concrete aggregates for light-stabilization of clay soils. *Construction and Building Materials, 227*. Doi: 10.1016/j.conbuildmat.2019.116792

Lekakh, S. N., Rawlins, C. H., Robertson, D. G. C., Richards, V. L., & Peaslee, K. D. (2008). Kinetics of Aqueous Leaching and Carbonization of Steelmaking Slag. *Metallurgical and Materials Transactions B, 39*(1), 125-134. Doi: 10.1007/s11663-007-9112-8

Li, Q., & Hu, J. (2020). Mechanical and Durability Properties of Cement-Stabilized Recycled Concrete Aggregate. *Sustainability, 12*(18). Doi: 10.3390/su12187380

Li, Y., Metcalf, J. B., Romanoschi, S. A., & Rasoulian, M. (1999). Performance and Failure Modes of Louisiana Asphalt Pavements with Soil–cement bases under Full-Scale Accelerated Loading. *Transportation Research Record*(1673), 9–15.

Liao, X. F., Chen, Z. D., Jiang, Y. J., & Lei, M. J. (2012). Research on cracking of cement-stabilized macadam base during highway construction. *J. Guangxi U. (Nat. Sci. Ed.)*(37), 716–722.

Limbachiya, M. C., Leelawat, T., & Dhir, R. K. (2000). Use Of Recycled Concrete Aggregate in high-strength concrete. *Materials and Structures, 33*, 574-580.

Liu, J., Yu, B., & Wang, Q. (2020). Application of steel slag in cement treated aggregate base course. *Journal of Cleaner Production, 269*. Doi: 10.1016/j.jclepro.2020.121733

Luxán, M., Sotolongo, R., Dorrego, F., & Herrero, E. (2000). Characteristics of the slags produced in the fusion of scrap steel by electric arc furnace. *Cement and Concrete Research, 30*, 517-519.

Maghool, F., Arulrajah, A., Ghorbani, B., & Horpibulsuk, S. (2022). Strength and permanent deformation properties of demolition wastes, glass, and plastics stabilized with foamed bitumen for pavement bases. *Construction and Building Materials, 320*. Doi: 10.1016/j.conbuildmat.2021.126108

Mahieux, P. Y., Aubert, J. E., & Escadeillas, G. (2009). Utilization of weathered basic oxygen furnace slag in the production of hydraulic road binders. *Construction and Building Materials, 23*(2), 742-747. Doi: 10.1016/j.conbuildmat.2008.02.015

Manso, J. M., Polanco, J. A., Losañez, M., & González, J. J. (2006). Durability of concrete made with EAF slag as aggregate. *Cement and Concrete Composites, 28*(6), 528-534. Doi: 10.1016/j.cemconcomp.2006.02.008

Maruyama, I., Sogo, M., Sogabe, T., Sato, R., & Kawai, K. (2004). Flexural properties of reinforced recycled beams. *Proceedings of international RILEM conference on the use of recycled materials in buildings and structures, 1*, 525–535.

Maslehuddin, M., Sharif, A. M., Shameem, M., Ibrahim, M., & Barry, M. S. (2003). Comparison of properties of steel slag and crushed limestone aggregate concretes. *Construction and Building Materials, 17*, 105-112.

Midgley, L., & Yeo, R. (2008). The development and evaluation of protocols for the laboratory characterisation of cemented materials. *Austroads Publication, No. AP–T101/08: 89.*

Mills-Beale, J., & You, Z. (2010). The mechanical properties of asphalt mixtures with Recycled Concrete Aggregates. *Construction and Building Materials, 24*(3), 230-235. Doi: 10.1016/j.conbuildmat.2009.08.046

Motz, H., & Geiseler, J. (2001). Products of Steel slags an opportunity to save natural resources.

Muhammad, B., Ismail, M., Bhutta, M. A. R., & Abdul-Majid, Z. (2012). Influence of non-hydrocarbon substances on the compressive strength of natural rubber latex-modified concrete. *Construction and Building Materials, 27*(1), 241-246. Doi: 10.1016/j.conbuildmat.2011.07.054

Naji, K. N., & Zaman, M. M. (2005). Flexural Properties of StabilizedAggregate Beams Subjected to Freeze–Thaw Cycles. *TRB 84th Annual Meeting Compendium of Papers CD-ROM.*

Nazir, R., Momeni, E., JahedArmaghani, D., & Amin, M. F. M. (2013). Correlation Between Unconfined Compressive Strength and Indirect Tensile Strength of Limestone Rock Samples. *Geotechnical Engineering, 18*, 1737-1746.

Netinger, I., Kesegic, I., & Guljas, I. (2011). The effect of high temperatures on the mechanical properties of concrete made with different types of aggregates. *Fire Safety Journal, 46*(7), 425-430. Doi: 10.1016/j.firesaf.2011.07.002

Nicolae, M., Vilciu, I., & Zaman, F. (2007). X-ray difraction analysis of steel slag and blast furance slag viewing their use for road construction. *U.P.B. Sci. Bull., Series B, 69*(2).

Noureldin, A., & McDaniel, R. (1990). Evaluation of steel slag asphalt surface mixtures. *Transportation Research Board 69th Annual Meeting, Washington, DC*.

Paige-Green, P., & Ware, C. (2011). Some Material and Construction Aspects Regarding in situ Recycling of Road Pavements in South Africa. *Road Materials and Pavement Design, 7*(3), 273-287. Doi: 10.1080/14680629.2006.9690038

Papayianni, I., & Anastasiou, E. (2010). Production of high-strength concrete using high volume of industrial by-products. *Construction and Building Materials, 24*(8), 1412-1417. Doi: 10.1016/j.conbuildmat.2010.01.016

Pasetto, M., & Baldo, N. (2011). Performance comparative analysis of stone mastic asphalts with electric arc furnace steel slag: a laboratory evaluation. *Materials and Structures, 45*(3), 411-424. Doi: 10.1617/s11527-011-9773-2

Poh, H. Y., Ghataora, G. S., & Ghazireh, N. (2006). Soil Stabilization Using Basic Oxygen Steel Slag Fines. *Journal of Materials in Civil Engineering, 18*(2), 229-240. Doi: 10.1061/(ASCE)0899-1561(2006)18:2(229)

Pourkhorshidi, S., Sangiorgi, C., Torreggiani, D., & Tassinari, P. (2020). Using Recycled Aggregates from Construction and Demolition Waste in Unbound Layers of Pavements. *Sustainability, 12*(22). Doi: 10.3390/su12229386

Pretorius, P. C., & Monismith, C. L. (1972). Fatigue Crack Formation and propagation in pavements containing soi-cement bases. *Highway Research Record, 407*, 102–115.

Qasrawi, H. (2014). The use of steel slag aggregate to enhance the mechanical properties of recycled aggregate concrete and retain the environment. *Construction and Building Materials, 54*, 298-304. Doi: 10.1016/j.conbuildmat.2013.12.063

Qasrawi, H., Shalabi, F., & Asi, I. (2009). Use of low CaO unprocessed steel slag in concrete as fine aggregate. *Construction and Building Materials, 23*(2), 1118-1125. Doi: 10.1016/j.conbuildmat.2008.06.003

Rashidi, M., Ashtiani, R. S., Si, J., Izzo, R. P., & McDaniel, M. (2018). A Practical Approach for the Estimation of Strength and Resilient Properties of Cementitious Materials. *Transportation Research Record*. Doi: 10.1177/0361198118769900

Reddy, A. S., Pradhan, R. K., & Chandra, S. (2006). Utilization of Basic Oxygen Furnace (BOF) slag in the production of a hydraulic cement binder. *International Journal of Mineral Processing, 79*(2), 98-105. Doi: 10.1016/j.minpro.2006.01.001

Rohde, L., Peres Núñez, W., & Augusto Pereira Ceratti, J. (2003). Electric Arc Furnace Steel Slag: Base Material for Low-Volume Roads. *Transportation Research Record: Journal of the Transportation Research Board, 1819*(1), 201-207. Doi: 10.3141/1819b-26

Sagoe-Crentsil, K. K., Brown, T., & Taylor, A. H. (2001). Performance of concrete made with commercially produced coarse recycled concrete aggregate. *Cement and Concrete Research, 31*, 701–712.

Sharba, A. A. (2019). The Efficiency of Steel Slag and Recycled Concrete Aggregate on the Strength Properties of Concrete. *Civil Engineering, 23*(11), 4846-4851. Doi: 10.1007/s12205-019-0700-3

Shayan, A., & Xu, A. (2003). Performance and properties of structural concrete made with recycled concrete aggregate. *ACI Materials Journal, 100*(5), 371–380.

Shen, D.-H., Wu, C.-M., & Du, J.-C. (2009). Laboratory investigation of basic oxygen furnace slag for substitution of aggregate in porous asphalt mixture.

Construction and Building Materials, 23(1), 453-461. Doi: 10.1016/j.conbuildmat. 2007.11.001

Shi, C. (2004). Steel slag: Its production, processing, characteristics, and cementitious properties. *Journal of Materials in Civil Engineering, 16*, 230-236. Doi: 10.1061/ (ASCE)0899-1561(2004)16:3(230)

Sofilic, T., Mladenovič, A., & Sofilič, U. (2011). Defining of Eaf Steel Slag Application Possibilities in Asphalt Mixture Production. *Journal of Environmental Engineering and Landscape Management, 19*(2), 148-157. Doi: 10.3846/ 16486897.2011.580910

Sounthararajah, A., Bui, H. H., Nguyen, N., Jitsangiam, P., & Kodikara, J. (2018). Early-Age Fatigue Damage Assessment of Cement-Treated Bases under Repetitive Heavy Traffic Loading. *Journal of Materials in Civil Engineering, 30*(6). Doi: 10.1061/ (asce)mt.1943-5533.0002250

Sudla, P., Donrak, J., Hoy, M., Horpibulsuk, S., Arulrajah, A., Rashid, A. S. A., . . . Samingthong, W. (2019). Laboratory Investigation of Cement-Stabilized Marginal Lateritic Soil by Crushed Slag–Fly Ash Replacement for Pavement Applications. *Materials in Civil Engineering, 32*(2). Doi: 10.1061/(ASCE) MT.1943-5533.0003011

Sudla, P., Horpibulsuk, S., Chinkulkijniwat, A., Arulrajah, A., Liu, M. D., & Hoy, M. (2018). Marginal lateritic soil/crushed slag blends as an engineering fill material. *Soils and Foundations, 58*. Doi: 10.1016/j.sandf.2018.03.007

Sukmak, G., Sukmak, P., Horpibulsuk, S., Yaowarat, T., Kunchariyakun, K., Patarapaiboolchai, O., & Arulrajah, A. (2020). Physical and mechanical properties of natural rubber modified cement paste. *Construction and Building Materials, 244*. Doi: 10.1016/j.conbuildmat.2020.118319

Tataranni, P., Sangiorgi, C., Simone, A., Vignali, V., Lantieri, C., & Dondi, G. (2018). A laboratory and field study on 100% Recycled Cement Bound Mixture for base layers. *International Journal of Pavement Research and Technology, 11*(5), 427-434. Doi: 10.1016/j.ijprt.2017.11.005

Tavakoli, M., & Soroushian, P. (1996). Strengths of aggregate concrete made using field-demolished concrete as aggregate. . *ACI Materials Journal, 93*(2), 182–190.

Theyse, H. L., De Beer, M., & Rust, F. C. (1996). overview of South african mechanicstic pavement design method. *Transportation Research Record*(1539), 6-17.

Thompson, M. R. (1986). Mechanicstic design concepts for stabilized base pavements. *University of Illinois.*

Tossavainen, M., Engstrom, F., Yang, Q., Menad, N., Lidstrom Larsson, M., & Bjorkman, B. (2007). Characteristics of steel slag under different cooling conditions. *Waste Manag, 27*(10), 1335-1344. Doi: 10.1016/j.wasman.2006.08.002

Tsakiridis, P. E., Papadimitriou, G. D., Tsivilis, S., & Koroneos, C. (2008). Utilization of steel slag for Portland cement clinker production. *J Hazard Mater, 152*(2), 805-811. Doi: 10.1016/j.jhazmat.2007.07.093

Vo, M. L., & Plank, J. (2018). Evaluation of natural rubber latex as film forming additive in cementitious mortar. *Construction and Building Materials, 169*, 93-99. Doi: 10.1016/j.conbuildmat.2017.12.098

Wang, Q., Yan, P., Yang, J., & Zhang, B. (2013). Influence of steel slag on mechanical properties and durability of concrete. *Construction and Building Materials, 47*, 1414-1420. Doi: 10.1016/j.conbuildmat.2013.06.044

Wen, H., & Ramme, B. (2008). *Performance Evaluation of Asphalt Pavement with Fly Ash Stabilized FDR Base: A Case Study*. Paper presented at the Airfield and Highway Pavements.

Xue, Y., Wu, S., Hou, H., & Zha, J. (2006). Experimental investigation of basic oxygen furnace slag used as aggregate in asphalt mixture. *J Hazard Mater, 138*(2), 261-268. Doi: 10.1016/j.jhazmat.2006.02.073

Yang, K.-H., Chung, H.-S., & Ashour, A. F. (2008). Influence of type and replacement level of recycled aggregates on concrete properties. *ACI Materials Journal, 105*(3), 289-296.

Yaowarat, T., Horpibulsuk, S., Arulrajah, A., Maghool, F., Mirzababaei, M., Rashid, A. S. A., & Chinkulkijniwat, A. (2020). Cement stabilization of recycled concrete aggregate modified with polyvinyl alcohol. *International Journal of Pavement Engineering*. Doi: 10.1080/10298436.2020.1746311

Yaowarat, T., Suddeepong, A., Hoy, M., Horpibulsuk, S., Takaikaew, T., Vichitcholchai, N., . . . Chinkulkijniwat, A. (2021). Improvement of flexural strength of concrete pavements using natural rubber latex. *Construction and Building Materials, 282*. Doi: 10.1016/j.conbuildmat.2021.122704

Yu, S. X., Wei, J. C., & Ma, S. J. (2011). Study on Fatigue Life of Lime Fly-Ash Treated Aggregate Based on SHRP Standard. *Advanced Materials Research, 261-263*, 111-114. Doi: 10.4028/www.scientific.net/AMR.261-263.111

Zalnezhad, M., & Hesami, E. (2020). Effect of steel slag aggregate and bitumen emulsion types on the performance of microsurfacing mixture. *Journal of Traffic and Transportation Engineering (English Edition), 7*(2), 215-226. Doi: 10.1016/j.jtte.2018.12.005

CHAPTER III

IMPROVED MECHANICAL AND MICROSTRUCTURE OF CEMENT-STABILIZED LATERITIC SOIL USING RECYCLED MATERIALS REPLACEMENT AND NATURAL RUBBER LATEX FOR PAVEMENT APPLICATIONS

3.1 Introduction

The pavement structure, comprising base and subbase layers beneath the surface layer (i.e., concrete or asphalt pavement) is normally built from natural aggregates such as natural quarry and granular aggregate materials. Lateritic soil (LS), which is abundantly available in tropical countries, is employed as an alternative pavement base/subbase material for the purpose of reducing the cost of road construction (Maichin et al., 2021; Osinubi & Nwaiwu, 2006). However, some natural LS have unfavorable characteristics when used as a road construction material. The mineralogical and structural alteration of LS is influenced by the duration of exposure to weathering and the subjected load, which leads to a change in engineering properties. A deep understanding of the structure and engineering behavior of LS is important for the usage of this material in highway construction.

The lessons learned from the previous research and practice demonstrated that the damage of LS base was due to the deterioration of the soil aggregate and its swelling behavior when subjected to the intense rainfall (Camapum de Carvalho et al., 2015; Toll & Caicedo, 2015). In addition, the longitudinal and transverse cracks of the pavement occurred when the tensile strength of the lateritic soil cannot resist the high volume of traffic load (Benatti & Miguel, 2013; Pessoa, 2004). Otálvaro, Neto, and Caicedo (2015) investigated the compressibility and microstructure of compacted lateritic soil for pavement application and indicated that the bimodal and grain size distribution were changed during compression and more than 50% of the broken soil aggregates caused the collapse of lateritic soil pavement. Some researchers have demonstrated that lateritic soils sometimes have unfavorable physical and mechanical properties such as high plasticity, substandard gradation, and low California bearing ratio (CBR), which do not always comply with the specifications for high volume roads designated by international or local road authorities (Horpibulsuk, Katkan, Sirilerdwattana, & Rachan, 2006; Maichin et al., 2021; Onyelowe, 2019; Otunyo & Chukuigwe, 2018; Sariosseiri & Muhunthan, 2009). As a result, improvement techniques have been applied for enhancing the quality of lateritic soils to achieve the required mechanical properties for pavement construction criteria. One of the cost-effective and widely used techniques is soil replacement with chemical stabilization method. In chemical stabilization, the interlocking between fine and coarse particles is enhanced by mixing unfavorable soils with high-quality coarse materials having an appropriate grain size distribution. A blend of 50%LS, 40% quarry aggregate, and 10% carbon black was reported to have the satisfied gradation and engineering properties for road base/subbase course (Tugume, Owani, Jjuuko, & Kalumba, 2018). The stabilizers including lime, fly-ash, and cement are commonly used in chemical stabilization method whilst Portland cement is preferred in most Southeast Asian countries because of the rapid improvement of mechanical properties at reasonable cost (Buritatun et al., 2020; Joel & Agbede, 2011; Phummiphan et al., 2016). The hydration products are generated within the void space of material grains and enhance mechanical properties of cement stabilized aggregates (Dafalla & Mutaz, 2012; Saeed & Hashim, 2018). The degree of improvement is affected by influential factors such as water/cement content, curing condition, and compaction effort (Horpibulsuk, Rachan, Chinkulkijniwat, Raksachon, & Suddeepong, 2010).

Mengue et al. (2017) indicated that 6% to 9% cement stabilized LS can be used as a pavement base as it satisfied the minimum strength requirement. In addition, remarkable shear strength improvement of cement stabilized LS was observed via triaxial loading test results. The effect of wetting-drying cycles on the durability of cement-LS mixture was investigated and found that the samples with 6% cement content could resist against 15 wetting-drying cycles, while the samples with higher cement content up to 12% can resist more cycles (Wahab et al., 2021). and Consoli, Párraga Morales, and Saldanha (2021); Joel and Agbede (2011) studied the mechanical properties of cement stabilized LS/sand blend at different sand replacement ratios (0, 15, 30, 45, and 60%) and cement contents (0, 3, 6, 9, and 12%). The Atterberg limits, CBR, and UCS of the cement stabilized LS/sand blends were improved with the increase of sand replacement ratio and cement content. The 6% cement and 45% sand replacement ratio were found to be the optimum ingredient for soil-cement-sand mixture as a pavement base.

To preserve natural resources and reduce the environmental burden, many researchers used the construction and demolition wastes including recycled concrete aggregate (RCA), recycled asphalt pavement (RAP), crushed brick (CB), and other industrial by-products including SS, plastic polyethylene terephthalate (Walker & Stace), calcium carbide residue (CCR) instead of the natural aggregates for a sustainable pavement application (Arulrajah, Mohammadinia, Phummiphan, Horpibulsuk, & Samingthong, 2016; Arulrajah, Perera, Wong, Horpibulsuk, & Maghool, 2020; Donrak et al., 2020; Jeerapan et al., 2019; Koohmishi & Palassi, 2022; Maghool, Arulrajah, Ghorbani, & Horpibulsuk, 2022). Furthermore, several studies have reported that SS and RCA can be deployed in pavement applications because their mechanical characteristics are evaluated to be similar or even superior to natural materials (Barišić, Dimter, & Rukavina, 2014; Ebrahim Abu El-Maaty Behiry, 2013; Hoy, Horpibulsuk, Rachan, Chinkulkijniwat, & Arulrajah, 2016; Maslehuddin, Sharif, Shameem, Ibrahim, & Barry, 2003; Qasrawi, 2014; Sudla et al., 2018). The UCS of cement stabilized 15%RCA-soil mixtures was reported to satisfy the minimum strength requirement as a subbase/subgrade for flexible and rigid pavement (Ebrahim Abu El-Maaty Behiry, 2013). Sudla et al. (2020; 2018) investigated the LS and crushed slag (Macsik & Jacobsson) blends stabilized by cement and fly ash (FA) as a pavement base. The CS replacement was found to improve the gradation and the resistance against Los Angeles abrasion and the soaked CBR of the blend, while reduce its liquid limit and plasticity index. In addition, the durability of cement and fly ash stabilized LS and CS blend against the wetting-drying cycles were also improved.

Even with its undeniable efficiency, cement stabilized material displays a shortcoming of brittle behavior, especially under compressive and tensile stresses (Correia, Venda Oliveira, & Custódio, 2015; Jamsawang, Voottipruex, & Horpibulsuk, 2015; Khattak & Alrashidi, 2006; Mengue et al., 2017; Wahab et al., 2021; Yaowarat, Suddeepong, et al., 2021). Pavement materials are commonly subjected to the tensile and flexural stresses caused by the wheel loads and the internal temperature. When the cement stabilized aggregate layers with low tensile and flexural strengths subject to these stresses, cracking takes place, which causes the reduction in the structural strength or the premature failure of the pavement. In addition, the water effortlessly enters the subgrade through the cracks, decreases the subgrade support and thereby hastens pavement deterioration. As a result, the service life of pavement structure is decreased.

Synthetic polymer additives including polyvinyl alcohol and asphalt emulsion were deployed to alleviate the limitations of cement-stabilized soils by enhancing the microstructure and mechanical properties of the mixtures. This leads to the improvement of serviceability and sustainability of road using cement-stabilized soil as a pavement material (Baghini, Ismail, Naseralavi, & Firoozi, 2016; Estabragh, Beytolahpour, & Javadi, 2011; Jose & Kasthurba, 2021; Tingle & Santoni, 2003; Yaowarat et al., 2022; Yaowarat, Sudsaynate, et al., 2021).

Natural rubber latex (NRL) is a natural polymer which has high elastic and tensile properties similar to synthetic polymer additives. Thailand is one of the largest producers of NRL worldwide. Besides exporting, the Thailand government also encourages research and development on using NRL in civil construction applications and especially in pavement applications as the road system in Thailand is rapidly growing. Indeed, NRL has been researched and proven to be effective in tensile and flexural strength improvement of cement mortar, cement paste, concrete, and cement-stabilized soils (Buritatun et al., 2020; Jose & Kasthurba, 2021; Muhammad, Ismail, Bhutta, & Abdul-Majid, 2012; G. Sukmak et al., 2020; Vo & Plank, 2018).

However, to the best of author's knowledge, the utilization of NRL as a polymer to improve the mechanical properties of cement stabilized lateritic soil with recycled aggregate replacement as pavement materials has not been studied. Using available in-situ LS in road construction can reduce the costs of transporting materials while the reuse of recycled aggregates can prevent the depletion of earth's natural resource and assist to offset environmental problem. For eco-friendly and cost-effective approach, this research attempts to ascertain the UCS and ITS of cement-NRL stabilized LS blended with SS and RCA as a sustainable pavement base material. Blending lateritic soil with SS and RCA can reduce fine contents and improve its particle contact strength. The cement content, dry rubber-to-cement (r/c) ratio, SS:LS ratio, and RCA:LS ratio were the influence factors investigated in this research. The microstructural analyses including scanning electron microscopy (SEM) and X-ray diffraction (XRD) were conducted to provide an insight into the influence factors on mechanical strength development. This research output will demonstrate the effective utilization of natural rubber latex and recycled materials for sustainable pavement technology.

3.2 Materials and methods

3.2.1 Materials

Original Portland cement was used in this research and its physical and mechanical properties are provided in Table 3.1. The natural rubber latex (NRL) obtained from the Rubber Authority of Thailand was used as a non-traditional additive. It was comprised of sodium dodecyl sulphate (SDS), zinc 2-mercaptobenzothiazole (ZMBT), zinc oxide, calcium carbonate. SDS was used as a surfactant to remove protein. ZMBT, zinc oxide, calcium carbonate, and sulphur substances can enhance the workability and properties of NRL. Table 3.2 shows the compositions of NRL; it was classified as the low dry rubber content (< 31%) (Muhammad et al., 2012).

Aggregates used this research included lateritic soil (LS), steel slag (SS), and recycled concrete aggregate (RCA). LS was collected from Nakhon Ratchasima province, Thailand, SS was obtained from Siam Steel Mill services Co., Ltd., Chonburi province, Thailand, and RCA was from the demolished concrete structures. The grain size distribution and engineering properties of aggregates are summarized in Figure 3.1 and Table 3.3, respectively, which were benchmarked with the national standards, Department of Highways (DOH), Thailand (DH-S201/2544, 2001; DH-S203/2556, 2013; DH-S204/2556, 2013; DH-S210/2547, 2004). These national standards are adopted from the standard specification for materials for soil-aggregate subbase, base, and surface courses according to ASTM D 1241 (ASTM-D1241, 2016), which is similar to AASHTO M 147-17 (AASHTO-M-147, 2017). LS had high fine content and its index properties did not compliance with the specification of DOH, Thailand. Although the Los Angeles abrasion value of LS was within the requirements for base material specified by DOH, Thailand, its Los Angles abrasion and soaked CBR value were found to be low. Similar research works suggested that the LS with low Los Angles abrasion required to blend with high-quality coarse aggregates to minimize the deterioration of the soil aggregates when subjected to cyclic traffic loading (Donrak et al., 2020; Phummiphan et al., 2018; 2016; Sudla et al., 2020). Therefore, LS must be blended with RCA/LS to improve physical and mechanical properties prior to cement stabilization for pavement applications. Table 3.4 shows the chemical compositions of LS, SS, and RCA obtained from the X-ray fluorescence (XRF) analysis. The major components of LS were SiO_2 (75.51%), Al_2O_3 (14.28%), and Fe_2O_3 (6.64%). The major components of SS and RCA were CaO, SiO_2, Al_2O_3, Fe_2O_3, and MgO. SS contained higher amount of Fe_2O_3 and MgO than RCA, while RCA had higher amount of CaO and SiO_2 than SS.

Table 3.1 Physical and chemical properties of Portland cement.

Properties of Portland cement	Values
Workability properties	
Initial setting time	101 min
Final setting time	188 min
Unconfined Compressive Strength (UCS)	
7-days UCS	24.7 MPa
28-days UCS	32.6 MPa
Chemical compositions in percent	
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 3.2 Properties of Natural Rubber Latex (NRL).

Properties	Values
Total solid content, %wt	33.06
Dry rubber content, %wt	30.79
Sludge content, %wt	2.46
Coagulum content, %wt	0.024
Specific garvity, G_s	0.96
pH	8

Table 3.3 Engineering properties of SS, RCA and LS.

Properties	SS	RCA	LS	Standard for base materials (DH-S201/2544)	Standard for stabilization of base materials (DH-S204/2532)
Largest particle size, mm	25	25	25	≤50	≤50
Los Angeles abrasion, %	17.2	31	34	≤40	≤60
Liquid limit, %	-	-	21	≤25	≤40
Plastic limit, %	-	-	8	≤6	-
Plasticity index, %	-	-	14	≤6	≤15
Specific gravity	3.64	2.57	2.78	-	-
Maximum dry density, kg/m^3	2700	1960	2130	-	-
Optimum water content, %	6.04	12	8.07	-	-
California bearing ratio	58	43	18.16	≥80	-
Water absorption of coarse-grained (%)	1.21	3.2	5.95	-	-
Water absorption of fine-grained (%)	4.53	5.3	4.2	-	-

Table 3.4 Chemical compositions of LS, SS, and RCA.

	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	MnO_2	TiO_2	SO_3	K_2O	Cr_2O_3
Materials	%									
LS	0.92	75.51	14.28	6.64	1.08	0.53	0.66	-	0.28	0.21
SS	22.24	25.47	4.95	34.61	3.74	5.35	0.28	1.97	0.048	1.05
RCA	52.48	36.40	3.08	2.87	1.62	0.09	0.21	1.18	0.13	-

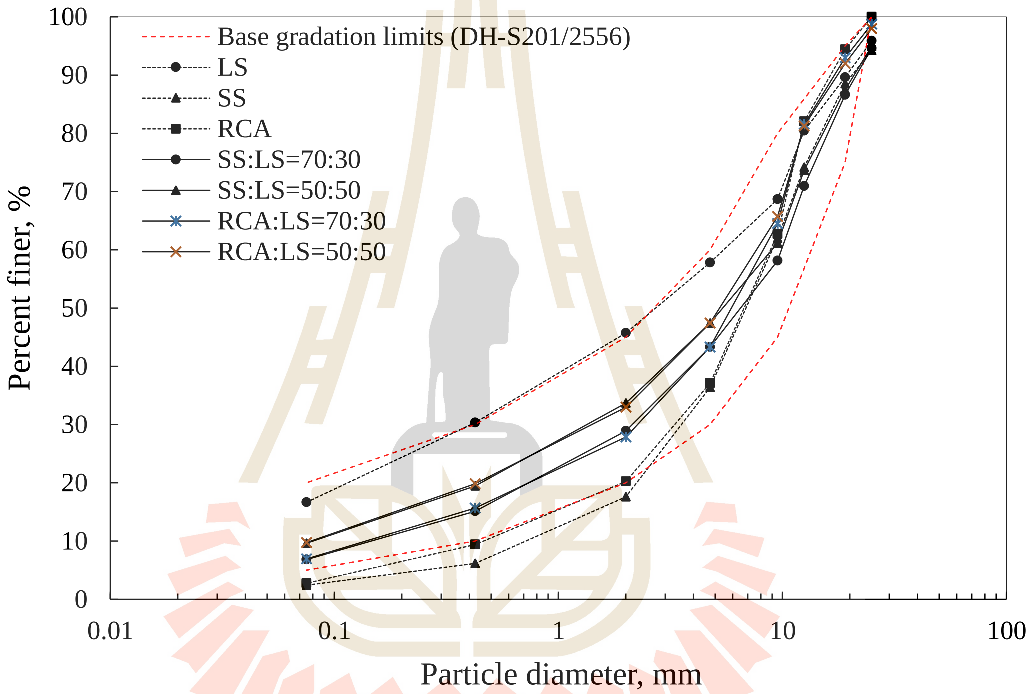


Figure 3.1 Particle grain size distribution.

3.2.2 Mix design

This research aims to evaluate the effect of NRL and the recycled aggregates (SS and RCA) replacement on the UCS and indirect tensile strength (ITS) of the cement-NRL stabilized blends as pavement base courses. The cement stabilized SS:LS and cement stabilized RCA:LS were prepared as controlled materials. The cement-NRL stabilized SS:LS and cement-NRL stabilized RCA:LS were prepared at dry rubber to cement (r/c) ratios of 3%, 5%, 10%, and 15%. The SS and RCA replacement ratios were SS:LS = 70:30 and 50:50, and RCA:LS = 70:30 and 50:50. The gradation curves of each blend were also presented in Figure 3.1. In this research, 5% cement content by weight practically used in Thailand was selected (DH-S203/2556, 2013).

Table 3.5 The ingredient and name of the studied mix design in this study.

Mixtures	SS (%)	RCA (%)	LS (%)	r/c* ratio
SS:LS=70:30, r/c = 0%	70	0	30	0
SS:LS=70:30, r/c = 3%	70	0	30	3
SS:LS=70:30, r/c = 5%	70	0	30	5
SS:LS=70:30, r/c = 10%	70	0	30	10
SS:LS=70:30, r/c = 15%	70	0	30	15
SS:LS=50:50, r/c = 0%	50	0	50	0
SS:LS=50:50, r/c = 3%	50	0	50	3
SS:LS=50:50, r/c = 5%	50	0	50	5
SS:LS=50:50, r/c = 10%	50	0	50	10
SS:LS=50:50, r/c = 15%	50	0	50	15
RCA:LS=70:30, r/c = 0%	0	70	30	0
RCA:LS=70:30, r/c = 3%	0	70	30	3
RCA:LS=70:30, r/c = 5%	0	70	30	5
RCA:LS=70:30, r/c = 10%	0	70	30	10
RCA:LS=70:30, r/c = 15%	0	70	30	15
RCA:LS=50:50, r/c = 0%	0	50	50	0
RCA:LS=50:50, r/c = 3%	0	50	50	3
RCA:LS=50:50, r/c = 5%	0	50	50	5
RCA:LS=50:50, r/c = 10%	0	50	50	10
RCA:LS=50:50, r/c = 15%	0	50	50	15

*5% cement content by weight

The sample preparation was commenced by mixing recycled aggregates (SS or RCA) with LS and cement thoroughly. The mixtures were then mixed with water to produce the cement-stabilized SS:LS and RCA:LS samples and mixed with water-

NRL to produce the cement-NRL stabilized SS:LS and RCA:LS samples. Table 3.5 summarizes the ingredient and name of the studied mix design in this study.

Modified compaction test was performed based on ASTM D1557 (ASTM-D1557, 2012) to obtain the maximum dry density (MDD) and optimum water content (OWC) of the studied blends. Thereafter, the samples prepared at the MDD and OWC were subjected to UCS test and ITS test. The unstabilized SS:LS blends and RCA:LS blends were also prepared and tested to evaluate the effect of cement on the UCS development.

3.2.3 Experimental program

a. Unconfined compressive strength (UCS) test

UCS test was conducted in accordance with ASTM D1633 (ASTM-D1633, 2017). The mold with 101.60 mm in diameter and 116.8 mm in height was used to prepare samples. Samples were cured in the mold for 24 hours before they were removed and wrapped by plastic films. They were then cured in a controlled temperature room at 25 ± 2^{o}C for 7- and 28 days (Figure 3.2). The UCS test was conducted with a vertical deformation rate of 1.0 mm per minute by using a compression machine. Three samples of each mixture were prepared and tested under the same condition to ensure the reliability of results.

b. Indirect tensile strength (ITS) test

ITS test is the prescribed method to measure the tensile characteristic, which is related to cracking resistance of cement stabilized aggregates. ITS samples were prepared using a mold with internal diameter of 101.60 mm and height of 63.5 mm under the same designed mixtures and curing conditions as UCS test (Figure 3.3). Based on ASTM D6931 (ASTM-D6931, 2017), the ITS test was also conducted on the compression test machine with a vertical deformation rate of one mm per minute.

For the mechanistical properties tests of the studied mixtures, at least three samples were prepared and tested for each mixture under the same testing conditions in order to ensure the data consistency. The results were reported with a low mean standard deviation (SD/x < 10%, where x is the mean strength value).

(a)

(b)

Figure 3.2 Photograph of (a) UCS samples in curing condition, (b) before and after UCS testing.

Figure 3.3 Photograph of ITS samples.

c. *Microstructural analysis*

SEM was performed to examine the growth of cementitious products in the samples. SEM samples were collected from broken fragments of the 28 days cured samples after UCS test. The liquid nitrogen was applied to immobilize the samples for about five minutes prior to evacuation at a pressure of 0.5 Pascal at -40°C for five days. The samples were then coated with gold prior to SEM analysis.

For the XRD analysis, the fragments of 28 days cured samples were collected, pulverized and passed through a 0.75 mm sieve to obtain the powder samples. Thereafter, they were oven-dried at 110°C for 24 hours before being subjected to XRD analysis. The powder samples were placed onto the X-ray diffractometer, and the readings were recorded for 2θ angles from 10° to 60°, and at an angular speed of 2°/min with a step size of 0.02.

3.3 Results and discussion

3.3.1 Compaction characteristics

The compaction characteristics (MDD and OWC) of the unstabilized samples, cement stabilized SS:LS and RCA:LS, and cement-NRL stabilized SS:LS and RCA:LS with different SS/RCA:LS ratios and r/c ratios are illustrated in Figure 3.4. For unstabilized samples, the 70SS:30LS blend had a higher MDD value than the 50SS:50LS blend whilst their OWC values were similar. Because the specific gravity of SS (G_s = 3.64) was higher than that of LS (G_s = 2.78), the MDD of SS:LS blends increased with the increased SS replacement. In contrast, the specific gravity of RCA (G_s = 2.57) was lower than that of LS. Hence, the 70RCA:30LS blend had lower MDD value than the 50RCA:50LS blend while the OWC of 70RCA:30LS blend was higher than that of 50RCA:50LS blend due to the higher water absorption of RCA. Moreover, the OWC value was more sensitive to the RCA replacement than the SS replacement.

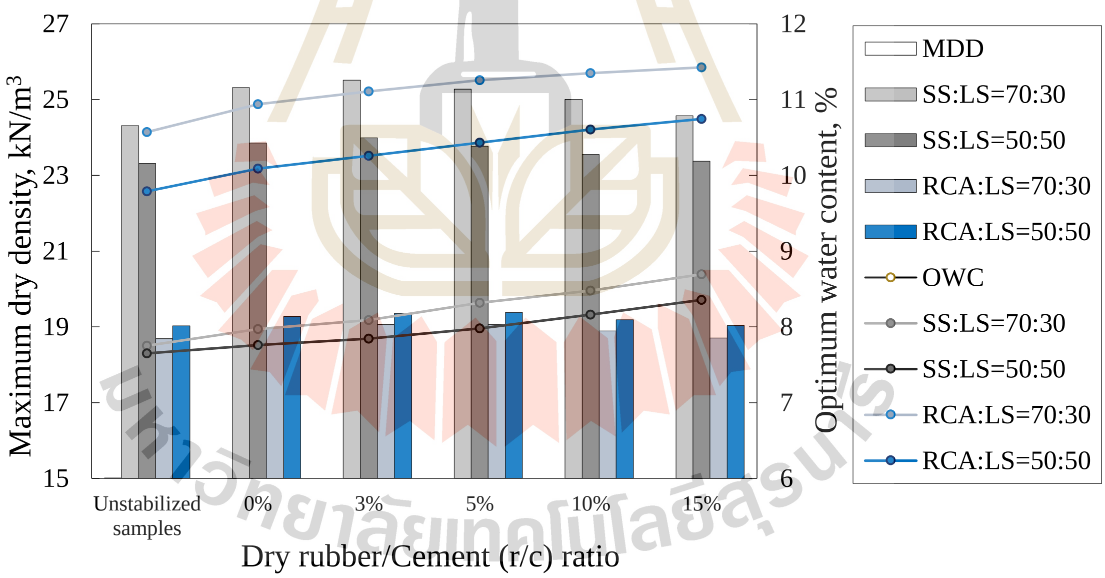


Figure 3.4 The illustration of compaction characteristics of mixtures.

The compaction behavior of the cement stabilized SS:LS and the cement stabilized RCA:LS (at r/c = 0%) was found to be similar to that of unstabilized samples while the MDD and OWC of the cement stabilized samples were higher. This is because more water is required for cement hydration and therefore it lubricates interparticle interaction between recycled aggregates and lateritic soils prior to the initial setting to develop the denser package and higher MDD. This result is in agreement with the previous finding (Buritatun et al., 2020; Horpibulsuk et al., 2006; Sariosseiri & Muhunthan, 2009).

The MDD and OWC values of cement-NRL stabilized SS:LS and RCA:LS samples at different r/c ratios are also demonstrated in Figure 3.4. The MDD of cement-NRL stabilized SS:LS and RCA:LS samples increased with the increased r/c ratio and reached the maximum values prior to the decrease of MDD. While the OWC of these samples gradually increased with the increased r/c ratio. The r/c ratio of 3% was found be optimum for cement-stabilized SS:LS samples at both SS:LS ratios of 70:30 and 50:50. Whereas the optimum r/c ratio for cement-stabilized RCA:LS samples at ratios of 70:30 and 50:50 was found to be the same at r/c ratio of 5%. This implies that the influence of NRL can enhance the compactability of cement stabilized material and lead to an increase in MDD. However, beyond the optimum r/c ratio, the undue solid form of NRL causes the reduction in MDD of the mixtures. This is because the NRL substance coagulates the mixtures and separates solid particles to form loose aggregation. The similar results were found in previous research studies on NRL modified soil-cement stabilization (Baghini, Ismail, & Bin Karim, 2015; Buritatun et al., 2020; Jose & Kasthurba, 2021).

The MDD of cement-NRL stabilized 70SS:30LS and 50SS:50LS samples was significantly higher than that of cement-NRL stabilized 70RCA:30LS and 50RCA:50LS samples at all r/c ratios. This is due to the specific gravity of the SS (G_s = 3.64) being higher than that of LS (G_s = 2.78) and RCA (G_s = 2.57). As a result, the higher SS and RCA replacement ratio contributed to the increase and the decrease in MDD of the SS:LS and RCA:LS blends, respectively, which has been previously reported by Sudla et al. (2018). On the other hand, the SS:LS blends had lower OWC than the RCA:LS blends because the SS had lower water absorption capacity than the RCA and the LS.

3.3.2 Unconfined compressive strength

Figure 3.5 summaries the UCS of cement stabilized SS:LS and RCA:LS and cement-NRL stabilized SS:LS and RCA:LS samples at different SS/RCA:LS ratios with various r/c ratios. The UCS of unstabilized SS:LS blends and RCA:LS blends were also presented to evaluate the effect of the cement stabilization. It is noteworthy that the UCS of both unstabilized blends increased with increasing the curing time. The 7- and 28-day UCS of pure LS was however found to be similar, which was 0.26 MPa and 0.28 MPa, respectively. This implied that unreacted cement particles in RCA and lime particles in SS could react with water and caused the UCS development over time. The UCS of unstabilized RCA:LS blends was higher than that of SS:LS blends at both 7 and 28 days of curing. This showed that the RCA had higher degree of chemical reaction, which could be attributed to the higher amount of CaO and SiO_2, detected by XRF analysis, of RCA when compared with SS.

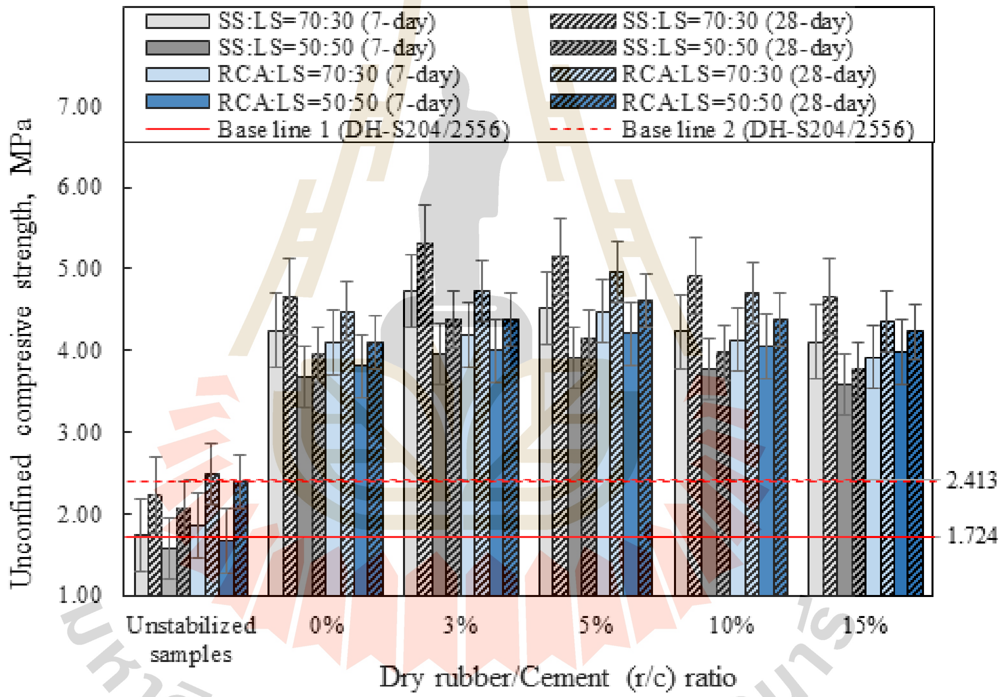


Figure 3.5 Unconfined compressive strength of unstabilized samples, cement- and cement-NRL stabilized SS:LS and RCA:LS samples at various r/c ratios.

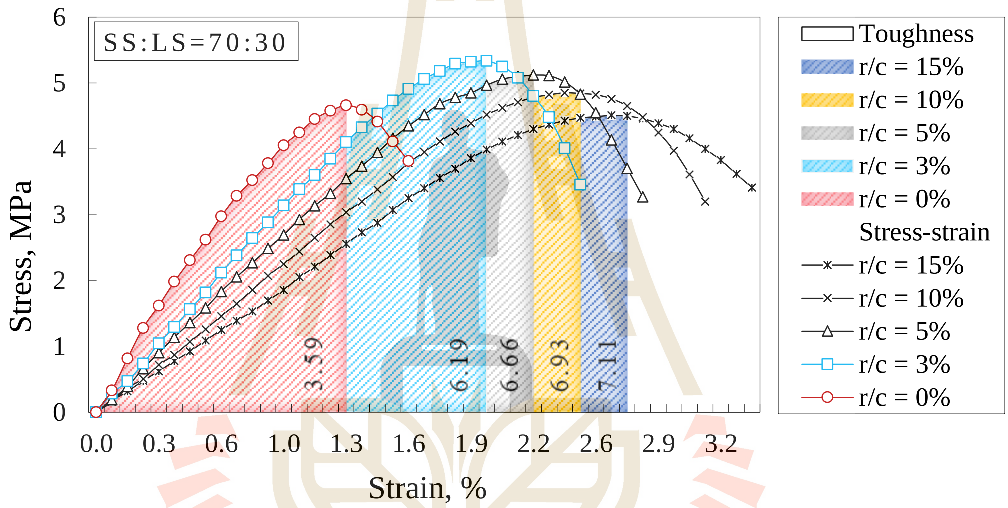
The 7-day UCS values of all cement stabilized SS:LS and RCA:LS samples at all r/c ratios were significantly higher than those of the unstabilized samples and the minimum requirement for both low traffic volume road (7-day UCS ≥ 1.724 MPa) and high traffic volume road (7-day UCS ≥ 2.413 MPa) specified by DOH, Thailand (DH-S204/2556, 2013). This might be attributed to the cement hydration products and

NRL films on the enhancement of interparticle bonding within the stabilized samples matrix.

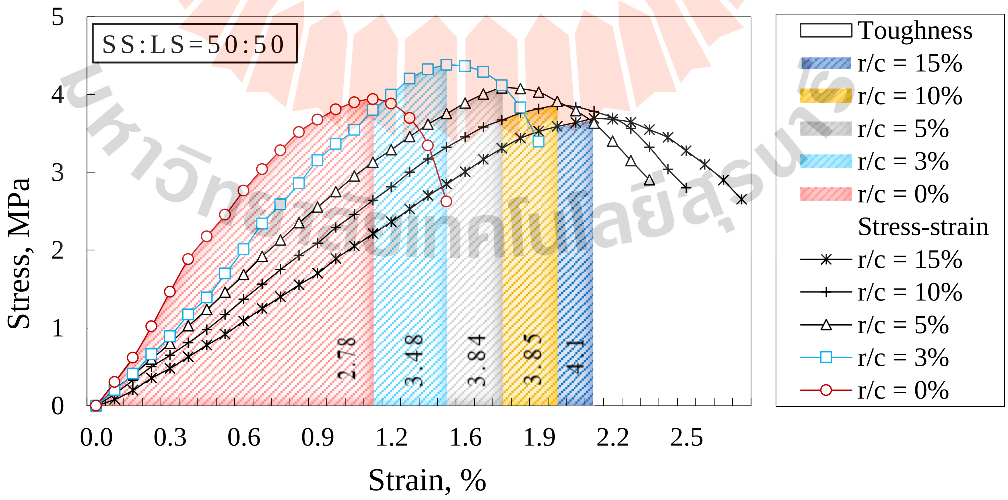
At a particular type of recycled aggregate, the cement stabilized blends with higher replacement ratios had higher 7-day UCS than the cement stabilized LS. The 7-day UCS of cement stabilized 70SS:30LS sample was higher than that of cement stabilized 70RCA:30LS sample while the 7-day UCS values of cement stabilized 50SS:50LS and 50RCA:50LS were found to be similar. Sudla et al. (2018) reported the low Los Angeles abrasion resistance of SS can enhance the engineering properties of SS and LS blends. In this research, the Los Angles abrasion of LS (34%) was higher than RCA (31%) and higher than SS (17.2%), which means the mechanical strength of SS was better than RCA and LS. As a result, the cement stabilized SS:LS had higher UCS value than the cement stabilized RCA:LS at the same recycled aggregate replacement ratios (SS:LS = 70:30 and RCA:LS = 70:30). Moreover, at all recycled aggregate replacement ratios, the UCS of cement stabilized SS:LS and RCA:LS samples increased with longer curing period. These findings were similar to the previous studies on the utilization of cement stabilized SS and RCA as pavement base/subbase materials in that the UCS of the stabilized LS increased with increasing the recycled aggregate content, cement content, and curing time (Barišić et al., 2014; Ebrahim Abu El-Maaty Behiry, 2013).

The UCS values of cement-NRL stabilized SS:LS and RCA:LS depend upon its r/c ratios and curing time. The UCS development trends of cement-NRL stabilized SS:LS and RCA:LS were found to be similar; UCS increased with increasing the r/c ratio until the maximum value at the optimum r/c ratio and then declined with further increase in r/c ratio. At the optimum r/c ratios, the UCS values of both cement-NRL stabilized SS:LS and RCA:LS samples were higher than those of the cement-stabilized SS:LS and RCA:LS (r/c ratio = 0%) samples. This confirms that the addition of NRL can enhance the cement stabilized SS/RCA and soil blends.

However, the optimum r/c ratio producing the maximum UCS of cement-NRL stabilized SS:LS and RCA:LS samples were found to be different. The highest UCS values of cement-NRL stabilized SS:LS and RCA:LS samples at all recycled aggregate replacement ratios cured for both 7 and 28 days were found at the optimum r/c ratio of 3% and 5%, respectively. At the optimum r/c ratio, the 7-day UCS of cement-NRL stabilized 70SS:30LS (r/c ratio = 3% and 70RCA:30LS (r/c ratio = 5%) samples was approximately 12% and 10.5% higher than that cement stabilized 70SS:30LS and 70RCA:30LS samples, respectively. Meanwhile, at the optimum r/c ratio, the 7-day UCS of cement-NRL stabilized 50SS:50LS (r/c ratio = 3%) and 50RCA:50LS (r/c ratio = 5%) samples was about 9% and 11% higher than cement stabilized 50SS:50LS and 50RCA:50LS, respectively. It is therefore worthwhile mentioning that at optimum r/c ratio, the percent improvement by NRL is practically the same even with different in replacement ratios and replacement materials.



(a)



(b)

Figure 3.6 Stress-strain curves of cement and cement-NRL stabilized SS:LS samples: (a) SS:LS=70:30 and (b) SS:LS=50:50.

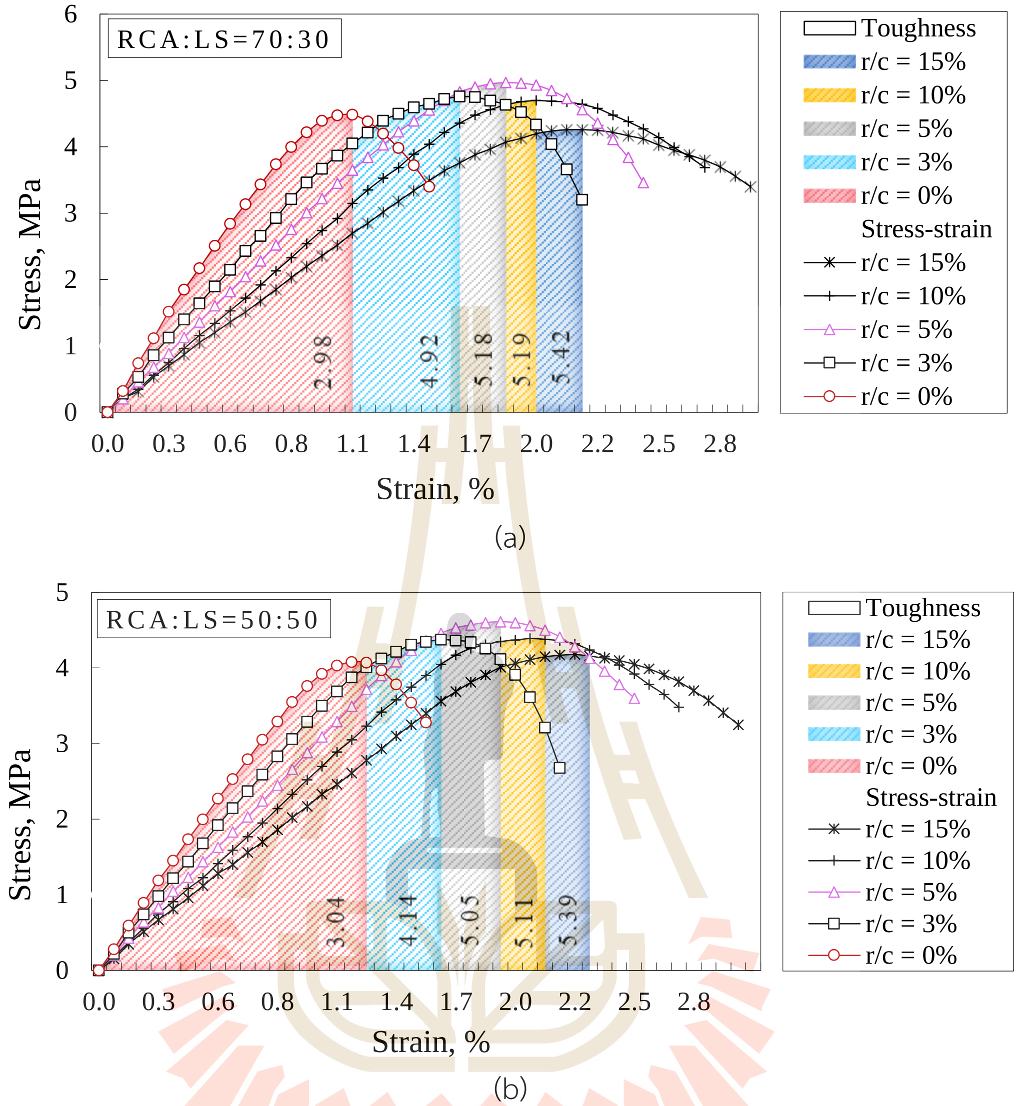


Figure 3.7 Stress-strain curves of cement and cement-NRL stabilized RCA:LS samples: (a) RCA:LS=70:30 and (b) RCA:LS=50:50.

Figures 3.6 and 3.7 demonstrate the stress and strain curves of cement- and cement-NRL stabilized SS:LS samples, and RCA:LS samples at age of 28 days, respectively. The UCS and ductility of both cement-NRL stabilized SS:LS and RCA:LS samples were found to be improved with the NRL additive when compared with those of the corresponding cement stabilized samples (r/c ratio = 0%). The higher strain at failure of all cement-NRL stabilized SS:LS samples and RCA:LS samples was found at the higher r/c ratio. This implied that the high elastic property of NRL additive played a significant role in improving the brittle behavior of cement stabilized samples. The toughness of the samples could be illustrated by the area under the stress-strain curve of the samples. It was clearly indicated that the cement-NRL stabilized samples exhibited higher toughness than the cement stabilized samples (without NRL additive); the toughness increased with the increased r/c ratio. This is a merit of cement-NRL stabilized recycled aggregate and soil blends as a pavement base subjected to cyclic loading of vehicles.

3.3.3 Indirect tensile strength

The ITS of cement stabilized SS:LS and RCA:LS samples and cement-NRL stabilized SS:LS and RCA:LS samples at different SS/RCA:LS ratios and various r/c ratios were evaluated and are shown in Figure 3.8. The 7- and 28-day ITS of pure LS was 0.11 MPa and 0.16 MPa, respectively. The ITS development pattern of cement stabilized SS:LS and RCA:LS samples and cement-NRL stabilized SS:LS and RCA:LS samples were found to be similar to the UCS development pattern. Indeed, the highest values of ITS were obtained at the optimum r/c ratios of 3% and 5% respectively for the cement-NRL stabilized SS:LS and cement-NRL stabilized RCA:LS samples. At the optimum r/c ratios, the values of ITS curing at 7 days of cement-NRL stabilized SS:LS and RCA:LS samples were approximately 10% higher than those of cement stabilized SS:LS and RCA:LS samples. This confirms that the addition of NRL can also empower the tensile strength of the cement stabilized recycled aggregate and soil blends.

The cement-NRL stabilized samples with higher recycled aggregate replacement ratios (SS:LS = 70:30 and RCA:LS = 70:30) exhibited higher ITS values than the samples with lower replacement ratios (SS:LS = 50:50 and RCA:LS = 50:50). In addition, the cement-NRL stabilized 70SS:30LS samples exhibited higher ITS values than that of cement-NRL stabilized 70RCA:30LS samples at the optimum r/c ratios. This is because SS had higher resistance to abrasion and angularness than RCA.

It was evident that the r/c ratio had a direct influence on both UCS and ITS of the studied blends. The maximum UCS and ITS values of 7-day and 28-day samples were obtained at the optimum r/c ratios of 3% and 5% respectively for cement-NRL stabilized 70SS:30LS and 50SS:50LS samples and cement-NRL stabilized 70RCA:30LS and 50RCA:50 samples. Figures 3.9 and 3.10 show the relationships between the 7-day UCS versus 28-day UCS and 7-day ITS versus 28-day ITS of the studied blends with and without NRL, respectively. The rate of UCS and ITS development over time was found to be the same for different replacement materials and replacement ratios. In general, the UCS and ITS development of cement stabilized materials is primarily governed by cement hydration products. This implies that the addition of NRL and replacement materials did not alter the rate of cementation bond strength over time of cement stabilized materials. Since both UCS and ITS development of cement stabilized materials are primarily dependent upon the cementation bond strength, it is on sound engineering principles and practices to establish the relationship between ITS and UCS for cement-NRL stabilized SS:LS and RCA:LS as shown in Figure 3.11. The ITS is commonly used to estimate the tensile or flexural cracking resistance of cement stabilized aggregate but the test is more complicated and time-consuming than the UCS test. The establishment of the correlation between UCS and ITS is therefore cost-effective and time-savings for geotechnical and pavement engineering design (Chhorn, Hong, & Lee, 2018; Din & Rafiq, 1997; Nazir, Momeni, Armaghani, & Amin, 2013; Wang, Chen, Xue, & Zhang, 2020). It is noted that the linear regression analysis exhibited the p-value < 0.000, which ensuring more than 95% confidence level of the developed models in Figure 3.9, 3.10 and 3.11.

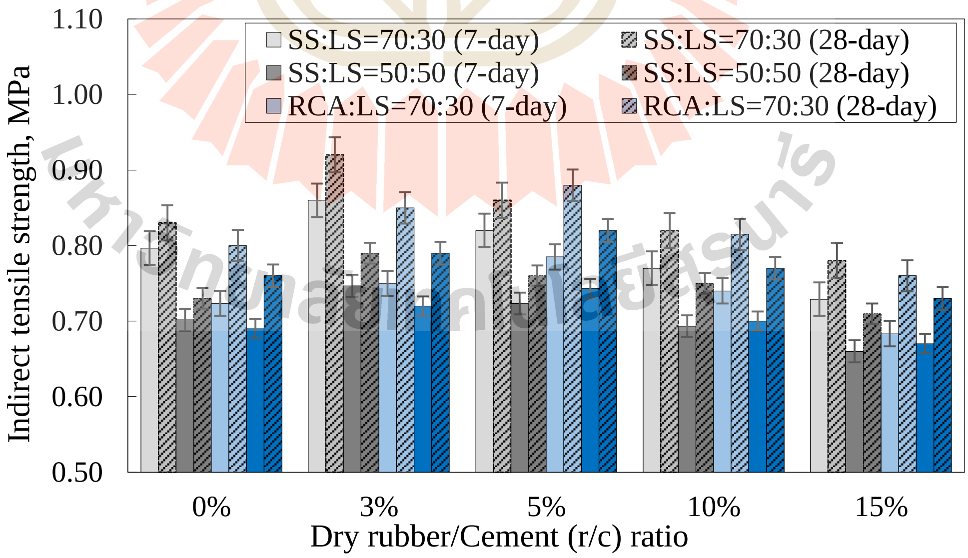
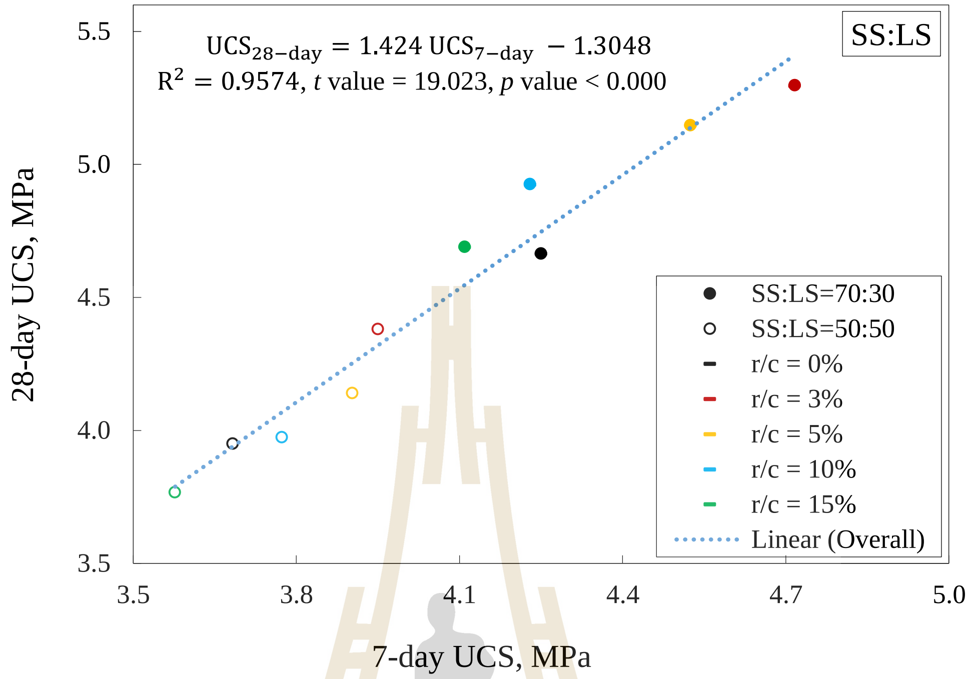
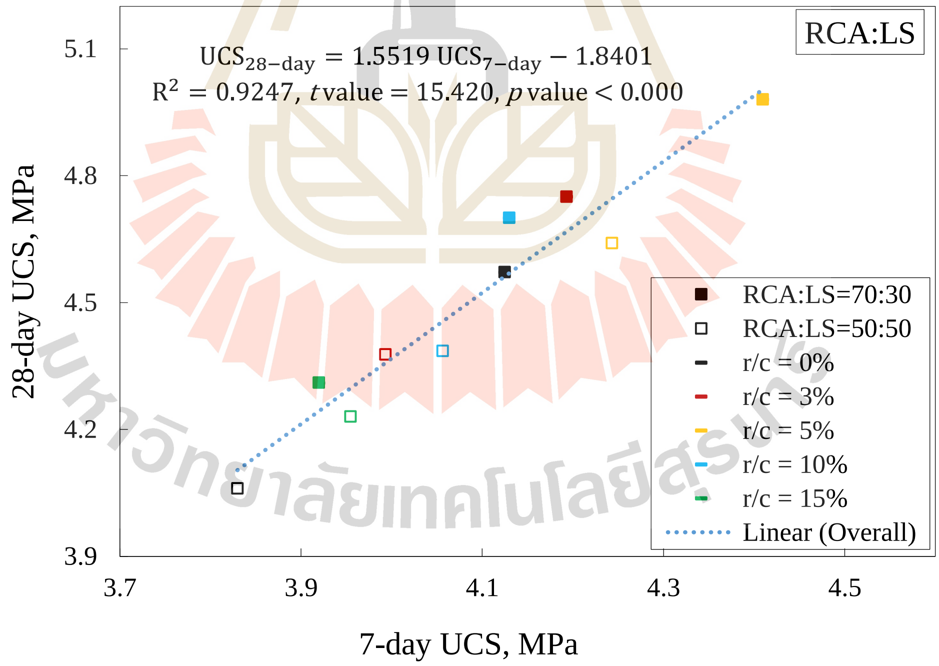


Figure 3.8 Indirect tensile strength of cement- and cement-NRL stabilized SS:LS and RCA:LS samples at various r/c ratios.

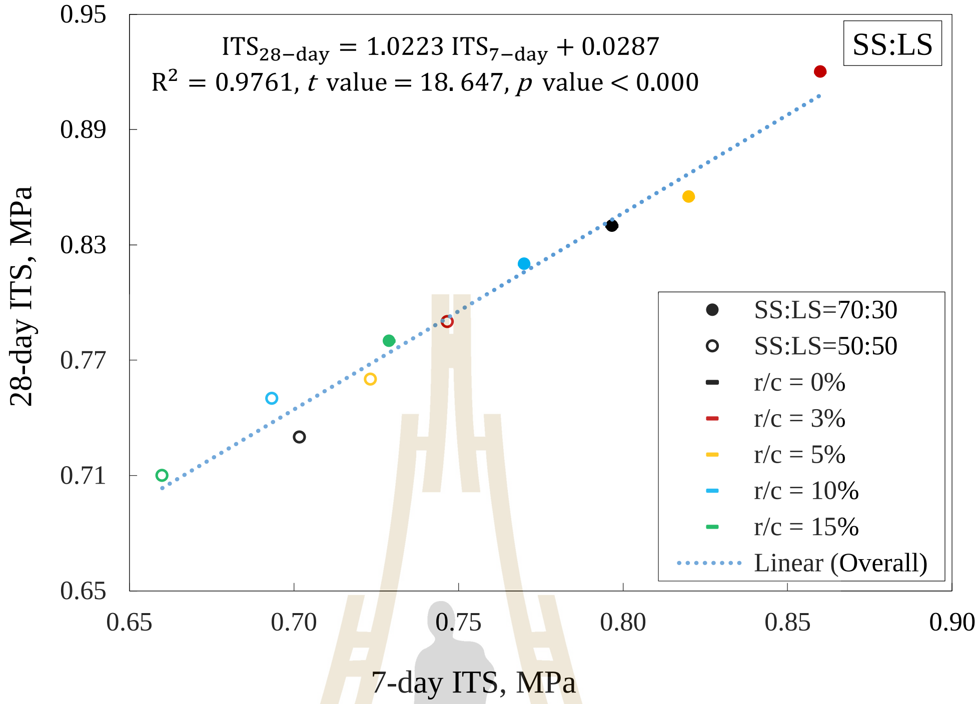


(a)

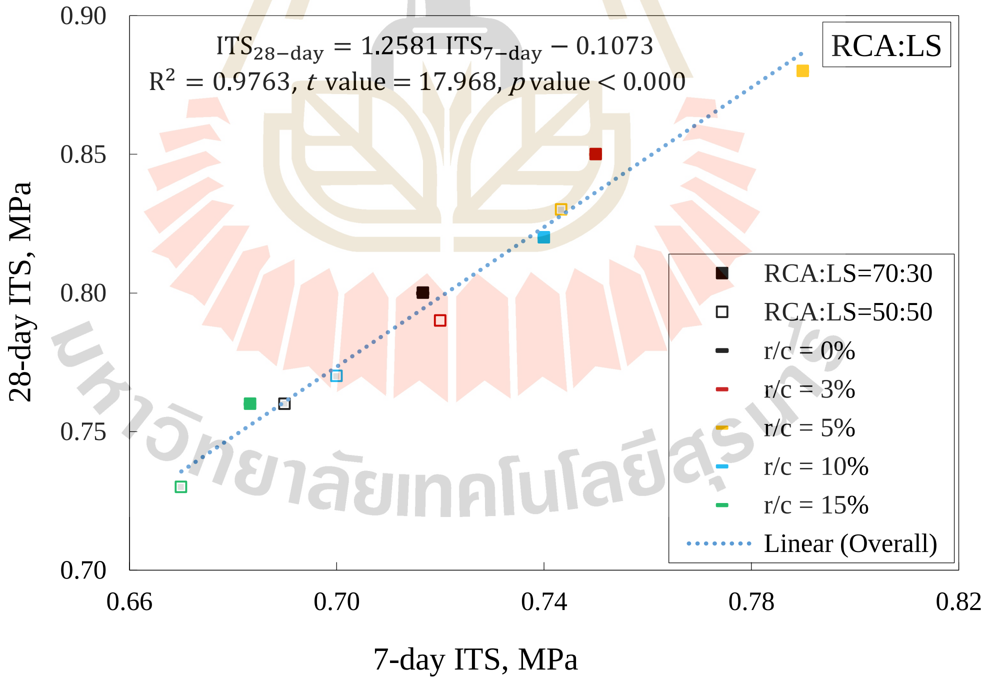


(b)

Figure 3.9 Relationship between 7-day and 28-day UCS of cement-NRL stabilized (a) SS:LS and (b) RCA:LS samples at different r/c ratios.

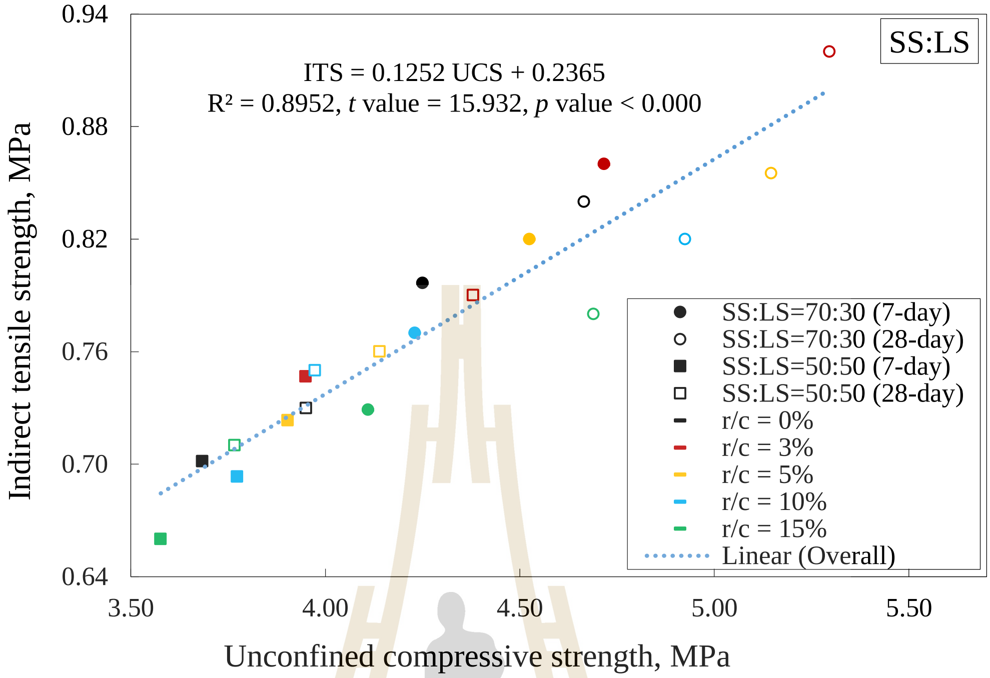


(a)

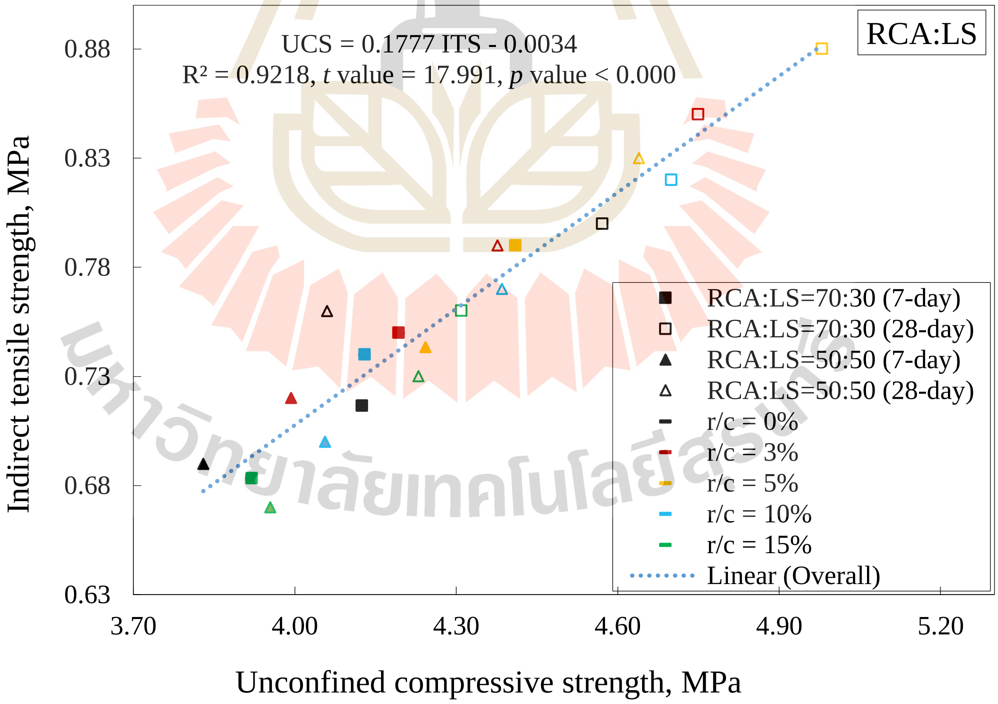


(b)

Figure 3.10 Relationship between 7-day and 28-day ITS of cement-NRL stabilized (a) SS:LS and (b) RCA:LS samples at different r/c ratios.



(a)



(b)

Figure 3.11 Relationship between ITS and UCS of cement-NRL stabilized (a) SS:LS and (b) RCA:LS samples.

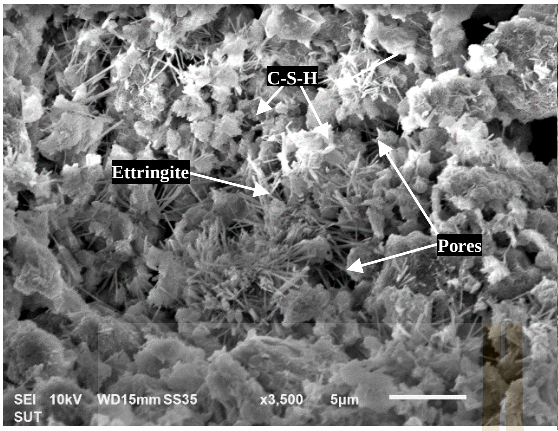
3.3.4 Microstructural analysis

a. Scanning electron microscopic analysis

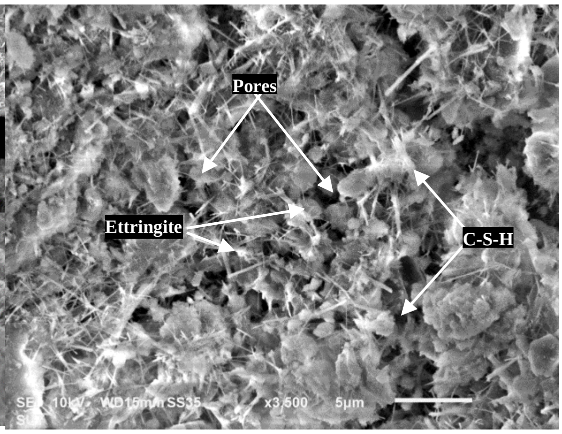
SEM analysis was conducted to inspect the change in microstructure of cement stabilized and cement-NRL stabilized samples, which cannot be observed by naked eyes. In this research, the cementitious products: calcium hydroxide (CH), calcium silicate hydrate (C-S-H), ettringite, NRL film, and pores are the important components to be examined. The change in soil structure associated with the interparticle bond strength, porosity and interconnected films is shown by the growth of cement hydration reaction and NRL film in pore spaces. Figure 3.12(a-f) illustrates the SEM images of cement stabilized and cement-NRL stabilized SS:LS and RCA:LS samples at an age of 28 days.

Figures 3.12a and 3.12b demonstrate SEM images of cement stabilized 70SS:30LS and 70RCA:30LS samples; the cementitious products were clearly detected in the pore space. The presence of cement hydration products resulted in the reduction of the void ratio and the increase of interparticle bond strength, which led to the development of mechanical strength (Horpibulsuk et al., 2010; Imtiaz, Ahmed, Hossain, & Faysal, 2020).

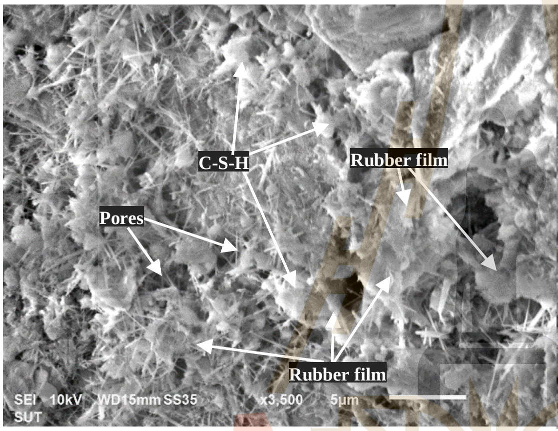
The SEM images of cement-NRL stabilized 70SS:30LS at optimum r/c ratio of 3% and cement-NRL stabilized 70RCA:30LS at optimum r/c ratio of 5% are shown in Figures 3.12c and 3.12d, respectively. The NRL films coexisted with the cementitious products were clearly detected in the pore space of the soil structures. In other words, the NRL film infiltrated the pore space that has not been filled by the cementitious products and resulted in the decrease in porosity. Consequently, UCS and ITS of the hardened cement-NRL stabilized blends were improved (Buritatun et al., 2020). However, a thicker NRL film network was generated from the excessive NRL volume, which was detected by SEM images of cement-NRL stabilized 70SS:30LS and 70RCA:30LS at r/c ratio of 15% (Figures 3.12e and 3.12f, respectively). The thicker films covered the cement grains and aggregates and acted as a barrier of water absorption, which might cause insufficient water for cement hydration. In other words, it retarded the hydration process and led to low UCS and ITS development of cement-NRL stabilized blends.



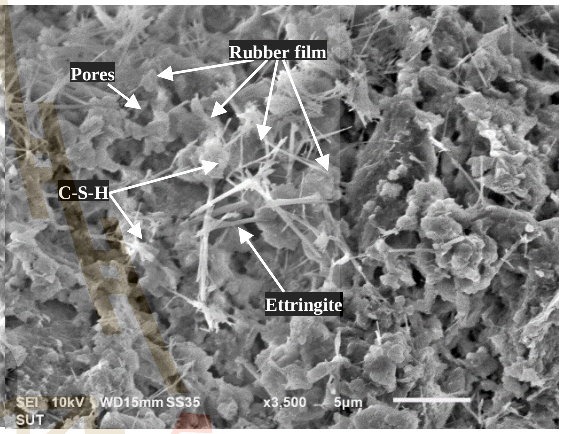
(a) SS:LS=70:30 at r/c ratio of 0%



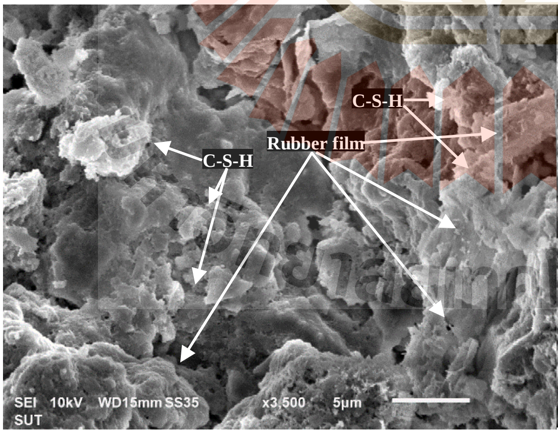
(b) RCA:LS=70:30 at r/c ratio of 0%



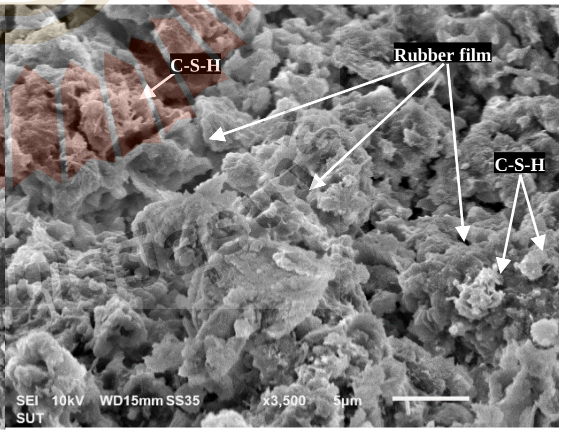
(c) SS:LS=70:30 at optimum r/c ratio of 3%



(d) RCA:LS=70:30 at optimum r/c ratio of 5%



(e) SS:LS=70:30 at maximum r/c ratio of 15%



(f) RCA:LS=70:30 at maximum r/c ratio of 15%

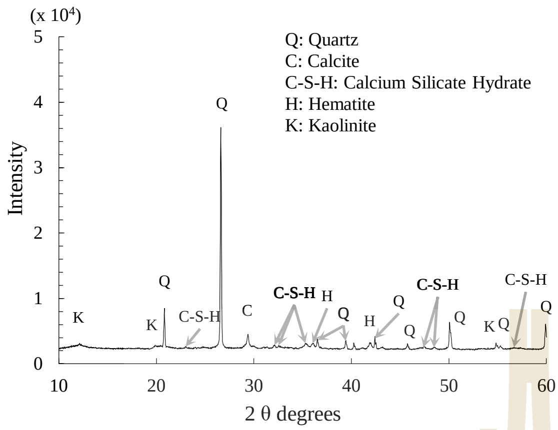
Figure 3.12 Scanning electron microscope images of cement stabilized and cement-NRL stabilized SS:LS and RCA:LS samples at ages of 28 days.

b. X-ray diffraction analysis

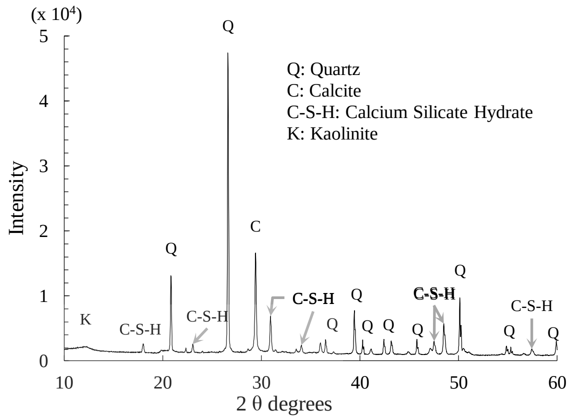
The mineralogical modifications in soil fabric can be analyzed by XRD analysis. The XRD patterns illustrate the amount of crystalline phase formation that represents the original aggregates and the cement hydrates. The X-axis in the pattern is in 2θ degree and the Y-axis is the intensity of the diffracted beam. Figure 3.13 shows XRD patterns of cement stabilized and cement-NRL stabilized 70SS:30LS and 70RCA:30LS samples at the optimum r/c ratio and on dry and wet sides of optimum. The XRD patterns illustrate main phases including quartz (SiO_2), calcite ($CaCO_3$), and calcium silicate hydrate (CaO-SiO_2-H_2O).

The mineralogy (XRD pattern) of cement stabilized 70SS:30LS and 70RCA:30LS was altered by the addition of NRL additive (compared Figure 3.13a-b to Figure 3.13c-f). It can be seen that the peak intensity of quartz and calcite were changed. They are the main compositions attribute to the carbonation of cement hydrates and result in mechanical strength development (Dafalla & Mutaz, 2012; Saeed & Hashim, 2018; P. Sukmak et al., 2019). It is evident from the XRD analysis that the cement hydration of both cement-NRL stabilized SS:LS and RCA:LS decreased with the increased rubber content. Similarly, the effect of latex polymer on the degree of cement hydration of cement-latex mortar and soil stabilization was found to be reduced with the increased solid rubber content (Diab, Elyamany, & Ali, 2013).

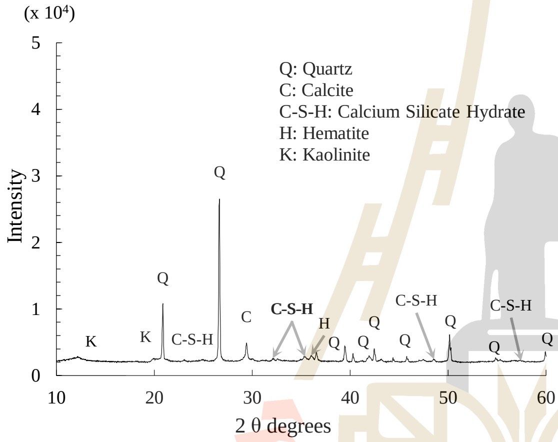
In addition, the variation of quartz (Si) and calcite (Ca), which are the dominant minerals governing the hydration of cement stabilization, was also discovered in this research. Kunther, Ferreiro, and Skibsted (2017) investigated the influence of the Ca/Si ratio on the UCS of cementitious products binders and indicated that the higher strength of cemented materials can be obtained at lower Ca/Si ratio. In this study, the Ca/Si ratio of cement stabilized SS:LS and RCA:LS samples was changed with the addition of NRL additive and was influenced by r/c ratio. It was clearly evident that the highest compressive and tensile strength values of cement-NRL stabilized SS:LS and RCA:LS at optimum r/c ratios were obtained at the lowest Ca/Si ratios as shown in Figure 3.14.



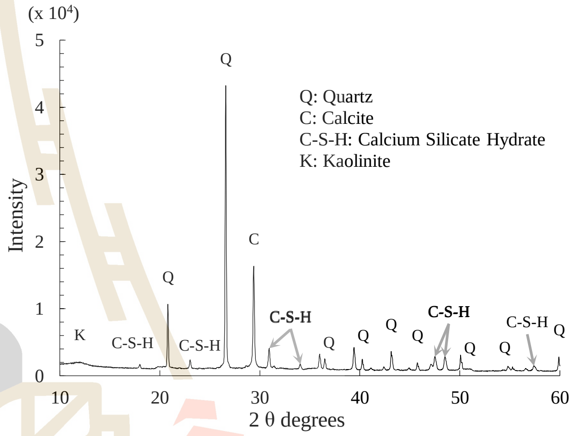
(a) SS:LS=70:30 at r/c ratio of 0%



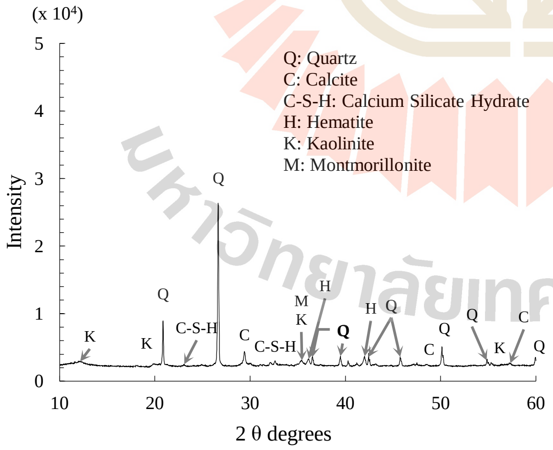
(b) RCA:LS=70:30 at r/c ratio of 0%



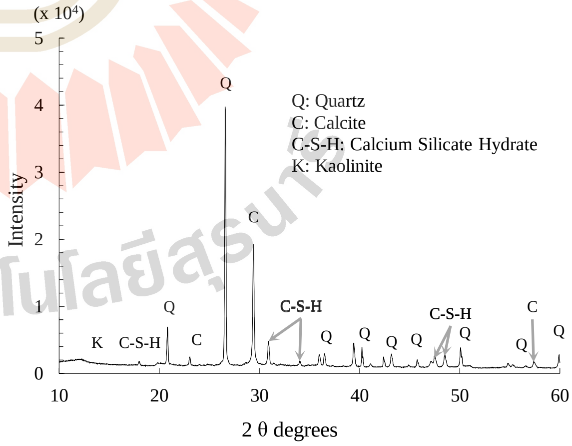
(c) SS:LS=70:30 at optimum r/c ratio of 3%



(d) RCA:LS=70:30 at optimum r/c ratio of 5%



(e) SS:LS=70:30 at maximum r/c ratio of 15%



(f) RCA:LS=70:30 at maximum r/c ratio of 15%

Figure 3.13 X-ray diffraction patterns of cement stabilized and cement-NRL stabilized SS:LS and RCA:LS samples at ages of 28 days.

SEM and XRD analyses confirmed that the UCS and ITS development of cement-NRL stabilized SS:LS and RCA:LS samples was influenced by the r/c ratio in which the samples at the excess NRL prevented the hydration process and hence fewer hydration products were detected, leading to the reduction of UCS and ITS. However, at the optimum r/c ratio, SEM images demonstrated that the cement-NRL mixture was improved by the formation of latex network (films) and membranes, resulted in the UCS and ITS development (Ohama, 1995).

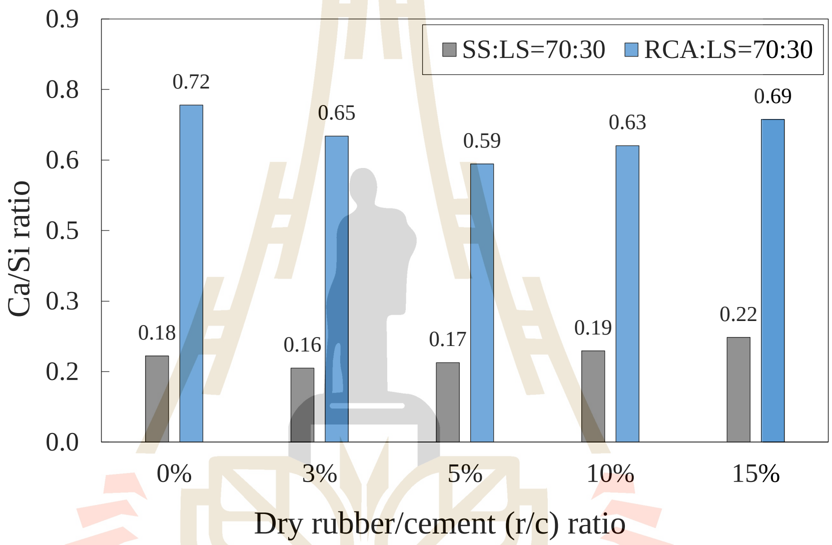


Figure 3.14 The variation of Ca/Si ratios of cement stabilized and cement-NRL stabilized SS:LS and RCA:LS at different dry rubber/cement ratios.

The results of this research illustrated the role of NRL in mechanical strength enhancement of cement-stabilized recycled aggregates and soil mixtures. With an appropriate amount of NRL, the interparticle bond strength and microstructure of samples are enhanced and therefore the mechanical strength is improved. This confirms that NRL can be used as a natural non-traditional additive in the sustainable stabilization of pavement base materials.

3.4 Conclusions

This study investigated the influence of NRL additive on UCS and ITS development of cement-stabilized lateritic soil (LS) with recycled aggregates such as

SS and RCA. The SS and RCA replacement ratios were SS:LS = 70:30, and 50:50, and RCA:LS = 70:30 and 50:50. The cement content of 5% by weight of aggregate and dry NRL to cement (r/c) of 0%, 3%, 5%, 10%, 15% were investigated. The SEM and XRD analyses were also conducted to ascertain the effect of the influence factors on their UCS and ITS development. The following are the significant conclusions obtained from this research:

1. The r/c ratios had the influence on the compactability, UCS, and ITS of cement-NRL stabilized SS:LS and RCA:LS blends. The optimum r/c ratios provided the lubrication of aggregate particles and led to the denser structure of the blends. The cement hydration reaction and film formation of NRL empower the interparticle bond strength and resulted in development in both UCS and ITS. The highest MDD, UCS, and ITS of cement-NRL stabilized SS:LS and RCA:LS blends were found at optimum r/c ratios. The optimum r/c ratios were found to be 3% for cement-NRL stabilized 70SS:30LS and 50SS:50LS samples, and 5% for cement-NRL stabilized 70RCA:30LS and 50RCA:50LS samples.

2. The UCS and ITS values of cement-NRL stabilized SS:LS and RCA:LS samples depend upon the r/c ratio and curing time. The UCS and ITS development patterns of cement-NRL stabilized SS:LS and RCA:LS were found to be similar; UCS and ITS increased with increasing the r/c ratio until the maximum value at the optimum r/c ratio and then declined with further increase in r/c ratio. At the optimum r/c ratios, the UCS and ITS values of both cement-NRL stabilized SS:LS and RCA:LS samples were higher than those of the cement-stabilized SS:LS and RCA:LS (r/c ratio = 0%) samples. This confirms that the addition of NRL can enhance the cement stabilized SS/RCA and soil blends. In addition, at a high replacement ratio of 70%, the UCS and ITS of cement-NRL stabilized SS:LS blends were higher than that of cement-NRL stabilized RCA:LS blends at the same optimum r/c ratio. This is because SS had higher resistance to abrasion and angularness than RCA.

3. The UCS and ITS development of cement-NRL stabilized SS:LS and RCA:LS blends were found to be reliant on the r/c ratio. Hence, the direct relationship between UCS and ITS of cement-NRL stabilized SS:LS and RCA:LS samples at various r/c ratios

with high reliability and accuracy could be established. This information is useful for predicting the mechanical strength for pavement engineering design.

4. SEM and XRD analyses confirmed that the hydration products of cement-NRL stabilized SS:LS and RCA:LS samples decreased with the increased NRL content. The excess NRL created a thicker NRL film network which covered the aggregate-cement matrix and retarded the hydration process. This led to the weaker structures and the drop of UCS and ITS. However, at the optimum r/c ratios, the coexistence between hydration products and the NRL films increased the interparticle bond strength and filled up the pore spaces. As a result, the void ratio of the cement-NRL stabilized blends was reduced, and therefore the UCS and ITS were improved.

3.5 References

AASHTO-M-147. (2017). Standard Specification for Materials for Aggregate and Soil–Aggregate Subbase, Base, and Surface Courses. In: American Association of State Highway and Transportation Officials (AASHTO).

Arulrajah, A., Mohammadinia, A., Phummiphan, I., Horpibulsuk, S., & Samingthong, W. (2016). Stabilization of Recycled Demolition Aggregates by Geopolymers comprising Calcium Carbide Residue, Fly Ash and Slag precursors. *Construction and Building Materials, 114*, 864-873. Doi: 10.1016/j.conbuildmat.2016.03.150

Arulrajah, A., Perera, S., Wong, Y. C., Horpibulsuk, S., & Maghool, F. (2020). Stiffness and flexural strength evaluation of cement stabilized PET blends with demolition wastes. *Construction and Building Materials, 239*, 117819. Doi: 10.1016/j.conbuildmat.2019.117819

ASTM-D1241. (2016). Standard Specification for Materials for Soil-Aggregate Subbase, Base, and Surface Courses, ASTM International, West Conshohocken, PA. In.

ASTM-D1557. (2012). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2,700 kN-m/m3)). West Conshohocken.

ASTM-D1633. (2017). Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders. West Conshohocken. In.

ASTM-D6931. (2017). Standard Test Method for Indirect Tensile (IDT) Strength of Asphalt Mixtures. West Conshohocken. In.

Baghini, M. S., Ismail, A., & Bin Karim, M. R. (2015). Evaluation of cement-treated mixtures with slow setting bitumen emulsion as base course material for road pavements. *Construction and Building Materials, 94*, 323-336. Doi: 10.1016/j.conbuildmat.2015.07.057

Baghini, M. S., Ismail, A., Naseralavi, S. S., & Firoozi, A. A. (2016). Performance evaluation of road base stabilized with styrene–butadiene copolymer latex and Portland cement. *International Journal of Pavement Research and Technology, 9*(4), 321-336. Doi: 10.1016/j.ijprt.2016.08.006

Barišić, I., Dimter, S., & Rukavina, T. (2014). Strength properties of steel slag stabilized mixes. *Composites Part B: Engineering, 58*, 386-391. Doi: 10.1016/j.compositesb.2013.11.002

Benatti, J. C. B., & Miguel, M. G. (2013). A proposal of structural models for colluvial and lateritic soil profile from southwestern Brazil on the basis of their collapsible behavior. *Engineering Geology, 153*, 1-11. Doi: 10.1016/j.enggeo.2012.11.003

Buritatun, A., Takaikaew, T., Horpibulsuk, S., Udomchai, A., Hoy, M., Vichitcholchai, N., & Arulrajah, A. (2020). Mechanical strength improvement of cement-stabilized soil using natural rubber latex for pavement base applications. *Journal of Materials in Civil Engineering, 32*(12), 04020372.

Camapum de Carvalho, J., de Rezende, L. R., Cardoso, F. B. d. F., Lucena, L. C. d. F. L., Guimarães, R. C., & Valencia, Y. G. (2015). Tropical soils for highway construction: Peculiarities and considerations. *Transportation Geotechnics, 5*, 3-19. Doi: 10.1016/j.trgeo.2015.10.004

Chhorn, C., Hong, S. J., & Lee, S. W. (2018). Relationship between compressive and tensile strengths of roller-compacted concrete. *Journal of Traffic and Transportation Engineering (English Edition), 5*(3), 215-223. Doi: 10.1016/j.jtte.2017.09.002

Consoli, N. C., Párraga Morales, D., & Saldanha, R. B. (2021). A new approach for stabilization of lateritic soil with Portland cement and sand: strength and durability. *Acta Geotechnica, 16*(5), 1473-1486. Doi: 10.1007/s11440-020-01136-y

Correia, A. A. S., Venda Oliveira, P. J., & Custódio, D. G. (2015). Effect of polypropylene fibres on the compressive and tensile strength of a soft soil, artificially stabilised with binders. *Geotextiles and Geomembranes, 43*(2), 97-106. Doi: 10.1016/j.geotexmem.2014.11.008

Dafalla, M., & Mutaz, E. (2012). Study of the mineralogical changes of clay due to cement and lime addition using X ray diffraction technique. *Res. J. Appl. Sci. Eng. Technol, 4*(19), 3746-3754.

DH-S201/2544. (2001). Standard for highway construction (Crush Rock Soil Aggregate Type), Department of Highways, Bangkok, Thailand. In.

DH-S203/2556. (2013). Standard for highway construction (Cement Modified Crushed Rock Base), Department of Highways, Bangkok, Thailand In.

DH-S204/2556. (2013). Standard for highway construction (Soil Cement Base), Department of Highways, Bangkok, Thailand In.

DH-S210/2547. (2004). Standard for highway construction (Crushed Slag), Department of Highways, Bangkok, Thailand. In.

Diab, A. M., Elyamany, H. E., & Ali, A. H. (2013). Experimental investigation of the effect of latex solid/water ratio on latex modified co-matrix mechanical properties. *Alexandria Engineering Journal, 52*(1), 83-98. Doi: 10.1016/j.aej.2012.11.002

Din, F., & Rafiq, M. (1997). Correlation between compressive strength and tensile strength/index strength of some rocks of North-West Frontier Province (limestone and granite). *Geological Bulletin, University of Peshawar, 30*, 183.

Donrak, J., Horpibulsuk, S., Arulrajah, A., Kou, H.-l., Chinkulkijniwat, A., & Hoy, M. (2020). Wetting-drying cycles durability of cement stabilised marginal lateritic soil/melamine debris blends for pavement applications. *Road Materials and Pavement Design, 21*(2), 500-518. Doi: 10.1080/14680629.2018.1506816

Ebrahim Abu El-Maaty Behiry, A. (2013). Utilization of cement treated recycled concrete aggregates as base or subbase layer in Egypt. *Ain Shams Engineering Journal, 4*(4), 661-673. Doi: 10.1016/j.asej.2013.02.005

Estabragh, A. R., Beytolahpour, I., & Javadi, A. A. (2011). Effect of Resin on the Strength of Soil-Cement Mixture. *Journal of Materials in Civil Engineering, 23*(7), 969-976. Doi: 10.1061/(ASCE)MT.1943-5533.0000252

Horpibulsuk, S., Katkan, W., Sirilerdwattana, W., & Rachan, R. (2006). Strength Development in Cement Stabilized Low Plasticity and Coarse Grained Soils: Laboratory and Field Study. *Soils and foundations, 46*(3), 351-366. Doi: 10.3208/sandf.46.351

Horpibulsuk, S., Rachan, R., Chinkulkijniwat, A., Raksachon, Y., & Suddeepong, A. (2010). Analysis of strength development in cement-stabilized silty clay from microstructural considerations. *Construction and Building Materials, 24*(10), 2011-2021. Doi: 10.1016/j.conbuildmat.2010.03.011

Hoy, M., Horpibulsuk, S., Rachan, R., Chinkulkijniwat, A., & Arulrajah, A. (2016). Recycled asphalt pavement – fly ash geopolymers as a sustainable pavement base material: Strength and toxic leaching investigations. *Science of the Total Environment, 573*, 19-26. Doi: 10.1016/j.scitotenv.2016.08.078

Imtiaz, T., Ahmed, A., Hossain, M. S., & Faysal, M. (2020). Microstructure Analysis and Strength Characterization of Recycled Base and Sub-Base Materials Using Scanning Electron Microscope. *Infrastructures, 5*(9), 70. Doi: 10.3390/ infrastructures5090070

Jamsawang, P., Voottipruex, P., & Horpibulsuk, S. (2015). Flexural Strength Characteristics of Compacted Cement-Polypropylene Fiber Sand. *Journal of Materials in Civil Engineering, 27*(9), 04014243. Doi: 10.1061/(ASCE)MT.1943-5533.0001205

Jeerapan, D., Menglim, H., Suksun, H., Arul, A., Mehdi, M., & A, R. A. S. (2019). Environmental assessment of cement-stabilised lateritic soil/melamine debris for Thailand's pavement. *Environmental Geotechnics, 0*(0), 1-7. Doi: 10.1680/ jenge.18.00195

Joel, M., & Agbede, I. O. (2011). Mechanical-Cement Stabilization of Laterite for Use as Flexible Pavement Material. *Journal of Materials in Civil Engineering, 23*(2), 146-152. Doi: 10.1061/(ASCE)MT.1943-5533.0000148

Jose, A., & Kasthurba, A. K. (2021). Laterite soil-cement blocks modified using natural rubber latex: Assessment of its properties and performance. *Construction and Building Materials, 273*, 121991. Doi: 10.1016/j.conbuildmat.2020.121991

Khattak, M. J., & Alrashidi, M. (2006). Durability and mechanistic characteristics of fiber reinforced soil–cement mixtures. *International Journal of Pavement Engineering, 7*(1), 53-62. Doi: 10.1080/10298430500489207

Koohmishi, M., & Palassi, M. (2022). Mechanical Properties of Clayey Soil Reinforced with PET Considering the Influence of Lime-Stabilization. *Transportation Geotechnics*, 100726. Doi: 10.1016/j.trgeo.2022.100726

Kunther, W., Ferreiro, S., & Skibsted, J. (2017). Influence of the Ca/Si ratio on the compressive strength of cementitious calcium–silicate–hydrate binders. *Journal of Materials Chemistry A, 5*(33), 17401-17412. Doi: 10.1039/c7ta06104h

Macsik, J., & Jacobsson, A. (1996). Leachability of V and Cr from LD-Slag/Portland Cement stabilised sulphide soil. *Waste Manag., 16*(8), 699–709.

Maghool, F., Arulrajah, A., Ghorbani, B., & Horpibulsuk, S. (2022). Strength and permanent deformation properties of demolition wastes, glass, and plastics stabilized with foamed bitumen for pavement bases. *Construction and Building Materials, 320*, 126108. Doi: 10.1016/j.conbuildmat.2021.126108

Maichin, P., Jitsangiam, P., Nongnuang, T., Boonserm, K., Nusit, K., Pra-Ai, S., . . . Aryupong, C. (2021). Stabilized High Clay Content Lateritic Soil Using Cement-FGD Gypsum Mixtures for Road Subbase Applications. *Materials, 14*(8), 1858. Doi: 10.3390/ma14081858

Maslehuddin, M., Sharif, A. M., Shameem, M., Ibrahim, M., & Barry, M. S. (2003). Comparison of properties of steel slag and crushed limestone aggregate concretes. *Construction and Building Materials, 17*(2), 105-112. Doi: 10.1016/S0950-0618(02)00095-8

Mengue, E., Mroueh, H., Lancelot, L., & Eko, R. M. (2017). Mechanical Improvement of a Fine-Grained Lateritic Soil Treated with Cement for Use in Road Construction. *Journal of Materials in Civil Engineering, 29*(11), 04017206. Doi: 10.1061/(ASCE)MT.1943-5533.0002059

Muhammad, B., Ismail, M., Bhutta, M. A. R., & Abdul-Majid, Z. (2012). Influence of non-hydrocarbon substances on the compressive strength of natural rubber latex-modified concrete. *Construction and Building Materials, 27*(1), 241-246. Doi: 10.1016/j.conbuildmat.2011.07.054

Nazir, R., Momeni, E., Armaghani, D. J., & Amin, M. M. (2013). Correlation between unconfined compressive strength and indirect tensile strength of limestone rock samples. *Electron J Geotech Eng, 18*(1), 1737-1746.

Ohama, Y. (1995). *Handbook of polymer-modified concrete and mortars: properties and process technology*: William Andrew.

Onyelowe, K. C. (2019). Nanosized palm bunch ash (NPBA) stabilisation of lateritic soil for construction purposes. *International Journal of Geotechnical Engineering, 13*(1), 83-91. Doi: 10.1080/19386362.2017.1322797

Osinubi, K. J., & Nwaiwu, C. M. (2006). Design of Compacted Lateritic Soil Liners and Covers. *Journal of Geotechnical and Geoenvironmental Engineering, 132*(2), 203-213. Doi: 10.1061/(ASCE)1090-0241(2006)132:2(203)

Otálvaro, I. F., Neto, M. P. C., & Caicedo, B. (2015). Compressibility and microstructure of compacted laterites. *Transportation Geotechnics, 5*, 20-34. Doi: 10.1016/j.trgeo.2015.09.005

Otunyo, A. W., & Chukuigwe, C. C. (2018). Investigation of the impact of palm bunch ash on the stabilization of poor lateritic soil. *Nigerian Journal of Technology, 37*(3), 600. Doi: 10.4314/njt.v37i3.6

Pessoa, F. H. C. (2004). Análises dos solos de Urucu para fins de uso rodoviário. *Distrito Federal*.

Phummiphan, I., Horpibulsuk, S., Rachan, R., Arulrajah, A., Shen, S.-L., & Chindaprasirt, P. (2018). High calcium fly ash geopolymer stabilized lateritic soil and granulated blast furnace slag blends as a pavement base material. *Journal of Hazardous Materials, 341*, 257-267. Doi: 10.1016/j.jhazmat.2017.07.067

Phummiphan, I., Horpibulsuk, S., Sukmak, P., Chinkulkijniwat, A., Arulrajah, A., & Shen, S.-L. (2016). Stabilisation of marginal lateritic soil using high calcium fly ash-based geopolymer. *Road Materials and Pavement Design, 17*(4), 877-891. Doi: 10.1080/14680629.2015.1132632

Qasrawi, H. (2014). The use of steel slag aggregate to enhance the mechanical properties of recycled aggregate concrete and retain the environment. *Construction and Building Materials, 54*, 298-304. Doi: 10.1016/j.conbuildmat.2013.12.063

Saeed, K. A., & Hashim, S. A. M. (2018). Micro-structural characterization of cement stabilized tropical Laterite clay soil contaminated by heavy metals. *Journal of Engineering and Sustainable Development (JEASD), 22*(2 (Part-2)).

Sariosseiri, F., & Muhunthan, B. (2009). Effect of cement treatment on geotechnical properties of some Washington State soils. *Engineering Geology, 104*(1-2), 119-125. Doi: 10.1016/j.enggeo.2008.09.003

Sudla, P., Donrak, J., Hoy, M., Horpibulsuk, S., Arulrajah, A., Rashid, A. S. A., . . . Samingthong, W. (2020). Laboratory Investigation of Cement-Stabilized Marginal Lateritic Soil by Crushed Slag–Fly Ash Replacement for Pavement Applications. *Journal of Materials in Civil Engineering, 32*(2), 04019353. Doi: 10.1061/(ASCE)MT.1943-5533.0003011

Sudla, P., Horpibulsuk, S., Chinkulkijniwat, A., Arulrajah, A., Liu, M. D., & Hoy, M. (2018). Marginal lateritic soil/crushed slag blends as an engineering fill material. *Soils and foundations, 58*(3), 786-795. Doi: 10.1016/j.sandf.2018.03.007

Sukmak, G., Sukmak, P., Horpibulsuk, S., Yaowarat, T., Kunchariyakun, K., Patarapaiboolchai, O., & Arulrajah, A. (2020). Physical and mechanical properties of natural rubber modified cement paste. *Construction and Building Materials, 244*, 118319. Doi: 10.1016/j.conbuildmat.2020.118319

Sukmak, P., Sukmak, G., Horpibulsuk, S., Setkit, M., Kassawat, S., & Arulrajah, A. (2019). Palm oil fuel ash-soft soil geopolymer for subgrade applications: strength and microstructural evaluation. *Road Materials and Pavement Design, 20*(1), 110-131. Doi: 10.1080/14680629.2017.1375967

Tingle, J. S., & Santoni, R. L. (2003). Stabilization of Clay Soils with Nontraditional Additives. *Transportation Research Record, 1819*(1), 72-84. Doi: 10.3141/1819b-10

Toll, D. G., & Caicedo, B. (2015). Special issue on lateritic and tropical geomaterials in construction of transportation infrastructures. *Transportation Geotechnics, 5*, 1-2. Doi: 10.1016/j.trgeo.2015.10.003

Tugume, B., Owani, I., Jjuuko, S., & Kalumba, D. (2018). *Performance of Lateritic Soils Stabilized with Both Crushed Rock Aggregates and Carbon Black as a Pavement Base Layer.* Paper presented at The International Congress on Environmental Geotechnics.

Vo, M. L., & Plank, J. (2018). Evaluation of natural rubber latex as film forming additive in cementitious mortar. *Construction and Building Materials, 169*, 93-99. Doi: 10.1016/j.conbuildmat.2017.12.098

Wahab, N. A., Roshan, M. J., Rashid, A. S. A., Hezmi, M. A., Jusoh, S. N., Nik Norsyahariati, N. D., & Tamassoki, S. (2021). Strength and Durability of Cement-Treated Lateritic Soil. *Sustainability, 13*(11), 6430.

Walker, P., & Stace, T. (1997). Properties of some cement stabilised compressed earth blocks and mortars. *Materials and Structures, 30*(9), 545-551. Doi: 10.1007/BF02486398

Wang, S., Chen, F., Xue, Q., & Zhang, P. (2020). Splitting Tensile Strength of Cement Soil Reinforced with Basalt Fibers. *Materials, 13*(14), 3110. Doi: 10.3390/ma13143110

Yaowarat, T., Horpibulsuk, S., Arulrajah, A., Maghool, F., Mirzababaei, M., Rashid, A. S. A., & Chinkulkijniwat, A. (2022). Cement stabilisation of recycled concrete aggregate modified with polyvinyl alcohol. *International Journal of Pavement Engineering, 23*(2), 349-357. Doi: 10.1080/10298436.2020.1746311

Yaowarat, T., Suddeepong, A., Hoy, M., Horpibulsuk, S., Takaikaew, T., Vichitcholchai, N., . . . Chinkulkijniwat, A. (2021). Improvement of flexural strength of concrete pavements using natural rubber latex. *Construction and Building Materials, 282*, 122704. Doi: 10.1016/j.conbuildmat.2021.122704

Yaowarat, T., Sudsaynate, W., Horpibulsuk, S., Chinkulkijniwat, A., Arulrajah, A., & Horpibulsuk, J. (2021). Mechanical Properties of Fly Ash–Asphalt Emulsion Geopolymer Stabilized Crushed Rock for Sustainable Pavement Base. *Journal of Materials in Civil Engineering, 33*(9), 04021220. Doi: 10.1061/(ASCE)MT.1943-5533.0003751

CHAPTER IV

IMPROVED FATIGUE PROPERTIES OF CEMENT-STABILIZED RECYCLED MATERIALS - LATERITIC SOIL USING NATURAL RUBBER LATEX FOR SUSTAINABLE PAVEMENT APPLICATIONS

4.1 Introduction

The base course is an essential component of the pavement structure that determines the quality and lifespan of the roads. In recent years, the significant increase in traffic load and volume has led to the shorter lifespan of the roads, which motivates researchers to conduct research concerning novel pavement improvement techniques. Cement, fly ash, lime, and slag are cementing binders that produce cementitious products through the hydration process to transfer the unfavored material into a strong bound pavement material. The cementitious products improve the strength of the structural base course by distributing the load over the larger area, hence the base layer's required thickness can be reduced.

Chemical stabilization of pavement materials is often considered for a cost-effective pavement design in Southeast Asia countries. Moffat et al. (1998) studied the performance comparison of bound and unbound granular pavement materials. It was reported that though the cost of stabilized materials might increase 2-3 times while its deformation resistance could be 6 - 10 times superior to the unbound layer. Portland cement is the most common binder used in chemical stabilization because of its convenience to implement in the field and its rapid improvement of mechanical properties (Horpibulsuk et al., 2006; 2010). Sobhan and Das (2007) indicated that cement hydration products enhance the chemical bonding of cement-stabilized materials and result in strength development. Arora and Aydilek (2005) and (Buritatum et al., 2020; 2022a) reported that the unconfined compressive strength (UCS) and indirect tensile resilient modulus (IT M_r) values of cement-stabilized soil materials could be increased with the increase of cement content. The pavement structure's stiffness affects the load distribution; the stiff cement-stabilized base can distribute traffic loads over a larger area, decreasing subgrade stresses and preserving the original grade for many years without expensive resurfacing or repairs (Christopher, Schwartz, & Boudreau, 2006).

Cement stabilization has been effectively applied to improve the properties of several materials, such as soils, granular materials, and recycled aggregates. Cement stabilization can increase cohesion of cohesionless soil, thus enhancing its strength and durability. Furthermore, cement stabilization can be used to improve expansive clayey soil's mechanical properties and mitigate linear shrinkage and water absorption (Firoozi et al., 2017). Horpibulsuk et al. (2006; 2010) also reported that the proper cement content could improve mechanical properties of silty clay, lateritic soil, and crushed rock.

To reduce the environmental burden from demolition and industrial wastes and save the construction cost, recycled materials such as recycled concrete aggregate (RCA) and steel slag (SS) have been widely utilized as aggregates in cement stabilization for sustainable pavement applications (Agrela et al., 2012; Arulrajah et al., 2020; Baghini et al., 2015; Barišić, Dimter, & Rukavina, 2015; Chakravarthi et al., 2019; Imtiaz et al., 2020; Li & Hu, 2020; Sariosseiri & Muhunthan, 2009). However, a rapid loss of moisture at early stage of cement stabilization leads to shrinkage and cracking of the pavement base course (Buritatum et al., 2022b). Hence, instead of cement usage as a single additive, synthetic polymers such as polyvinyl alcohol and asphalt emulsion have been used as a compound additive to enhance the microstructural and tensile/flexural properties of cement-stabilized base materials (Baghini et al., 2016; Estabragh, Beytolahpour, & Javadi, 2011; Li et al., 2020; Tingle & Santoni, 2003; Yaowarat et al., 2020; 2021).

One of the natural polymers that have been commonly used in recent research is natural rubber latex (NRL), which has demonstrated effectiveness in enhancing the strength and durability of cement stabilization because of its high elastic and tensile properties (Buritatum et al., 2020; Buritatum et al., 2022a; Jose & Kasthurba, 2020; Tran et al., 2022). Tran et al. (2022) investigated the UCS development of cement-NRL stabilized lateritic soil with RCA and SS replacement and illustrated that the UCS meets the minimum strength requirement designated by the Department of Highways (DOH), Thailand as a base material. However, in the field condition, repetitive stress by the traffic loads is generated instead of unconfined compressive stress; the UCS alone may not apply to the actual situations (Khoury & Zaman, 2007; Thompson & Smith, 1990). The cyclic traffic loads typically cause vertical compressive and horizontal tensile stresses in the pavement base layer (Kavussi & Modarres, 2010). The cumulative irreversible deformation caused over time by repeated tensile stress eventually leads to fatigue-cracking failure (Sobhan & Das, 2007). Several studies demonstrated the importance of fatigue properties of cement-stabilized base materials for pavement thickness design; the selected base material must withstand the critical repeated loads and prevent excessive permanent deformation during the service lifetime (Bhogal et al., 1995; Biswal, Sahoo, & Dash, 2020b; Jitsangiam, Nusit, Chummuneerat, Chindaprasirt, & Pichayapan, 2016a; Lv et al., 2019; Pretorius & Monismith, 1972; Sounthararajah, Bui, Nguyen, Jitsangiam, & Kodikara, 2018; Werkmeister, 2003; Wilmot & Rodway, 1999). The parameters that affect the tensile properties of cement stabilized materials were investigated previously (Consoli, Marques, Floss, & Festugato, 2017; Festugato, Venson, & Consoli, 2021). Festugato et al. (2021) found that the resilient modulus and fatigue life were directly proportional to the cement content and inversely proportional to the porosity of cement-stabilized sand. Consoli et al. (2017) established the generalized function to assess the strength values at various porosities and cement contents.

The tensile strength and stiffness modulus of the materials are essential for pavement design following the mechanistic-empirical pavement design guideline. The pavement thickness design is based on the fatigue-cracking failure criteria, which is obtained from a relationship between tensile strain and fatigue life of the cement-stabilized material. The tensile property of cement-stabilized materials can be measured by direct or indirect tensile, and flexural beam tests. The test under cyclic flexural stress is considered as the most important condition for evaluating the fatigue response (Rao et al., 1990). However, several researchers have recommended indirect tensile testing instead as a cost and time effective method (Bullen, 1994; Piratheepan, Gnanendran, & Lo, 2010).

Therefore, to investigate the effective utilization of natural rubber latex in cement- stabilized lateritic soil with RCA and SS as pavement base materials, the indirect tensile resilient modulus and indirect tensile fatigue life under cyclic load conditions were performed. The relationship between the UCS, ITS, IT-M_r, permanent deformation, and fatigue life of those cement-stabilized lateritic soil with different recycled aggregate replacements was established, which are viral parameters for structural pavement design in the mechanistic empirical approach.

4.2 Materials and methods

4.2.1 Materials

Aggregates of this research included lateritic soil (LS), steel slag (SS), and recycled concrete aggregate (RCA). LS and SS were collected from Nakhon Ratchasima province and Siam Steel Mill Services Co., Ltd., Chonburi province, Thailand, respectively while RCA was obtained from crushed concrete structures in Nakhon Ratchasima province. Figure 4.1 shows the grain size distribution of LS, SS, and RCA and compares it with the base gradation limits designed by the Department of Highways (DOH), Thailand, similar to AASHTO M 147. The liquid limit and plastic limit of LS were 21% and 8%, respectively, while the SS and RCA were non-plastic material. The LS, RCA, and SS had a specific gravity of 2.78, 2.57, and 3.64, respectively. The maximum dry unit weight of LS, RCA, and SS was 21.30 kN/m^3, 19.60 kN/m^3, and 27.00 kN/m^3, respectively, at the optimum water content of 8.1, 12.0, and 6.05%. LS, RCA, and SS had a Los Angeles abrasion value of 34, 31, and 17.2%, respectively, and were lower than the maximum allowance of 40% specified by DOH, Thailand. The aggregate material required a minimum California bearing ratio (CBR) of 80% to meet the standard requirement for base material designed by DOH, Thailand (DH-S201/2544). The CBR of LS, RCA, and SS was 18, 43, and 58%, respectively, and lower than the minimum requirement; hence the cement is used to stabilize these materials following the DOH, Thailand guideline for cement stabilization of base materials.

Ordinary Portland cement having 7-day and 28-day compressive strengths of 24.7 MPa and 32.6 MPa, respectively, was used in this research. Natural rubber latex (NRL) in a liquid form comprised total solid content of 33.06, dry rubber content of 30.8, sludge content of 2.46, and coagulum content of 0.024 percent by weight, which is classified as the low category rubber latex. The specific gravity and pH of NRL were 0.96 and 8, respectively.

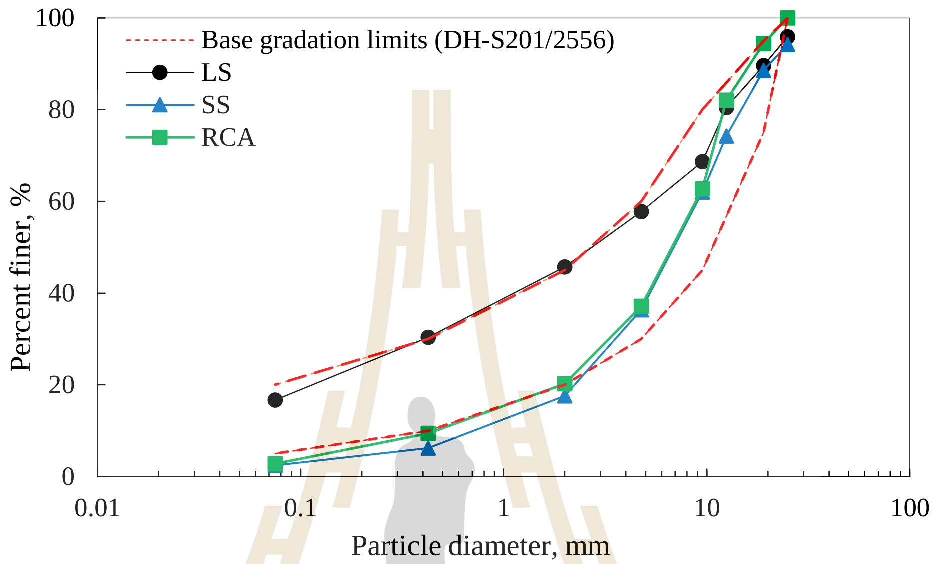


Figure 4.1 Grain size distribution of LS, SS, and RCA.

4.2.2 Samples preparation

The air-dried LS, SS, and RCA materials were passed through a 19-mm sieve to remove coarser particles before being used in this research. In this study, LS was replaced with 70% and 50% of recycled aggregates to design four blends, namely 70SS:30LS, 50SS:50LS, 70RCA:30LS, and 50RCA:50LS. The cement content (5% by weight) was used for the cement stabilization. Each blend was thoroughly mixed with cement and followed by water to manufacture cement-stabilized SS/RCA:LS samples. Similarly, the blends were mixed with uniform water-NRL liquid to manufacture cement-NRL stabilized SS/RCA:LS samples. The samples were prepared by compaction at maximum dry density (MDD) and optimum liquid content (OLC) in a cylindrical mold with dimensions of 101.6 mm in diameter and 63.5 mm in height, which were predetermined from the modified compaction test (ASTM-D1557-12, 2012). The samples along with the mold were kept in a controlled temperature room (humidity of 95% and temperature of 25°C) for 24 hours before being demolded and wrapped with the plastic sheet. After 28 days of curing, the samples were subjected to the mechanical strength and fatigue tests. The mechanical strength tests included UCS and ITS, while the fatigue tests included indirect tensile resilient modulus and indirect tensile fatigue. The mixed design showing the ingredient of the studied materials is demonstrated in Table 4.1.

Table 4.1 The ingredient of mixed design in this study.

Mixtures	SS (%)	RCA (%)	LS (%)	r/c* ratio
SS:LS=70:30, r/c = 0%	70	0	30	0
SS:LS=70:30, r/c = 3%	70	0	30	3
SS:LS=70:30, r/c = 5%	70	0	30	5
SS:LS=70:30, r/c = 10%	70	0	30	10
SS:LS=70:30, r/c = 15%	70	0	30	15
SS:LS=50:50, r/c = 0%	50	0	50	0
SS:LS=50:50, r/c = 3%	50	0	50	3
SS:LS=50:50, r/c = 5%	50	0	50	5
SS:LS=50:50, r/c = 10%	50	0	50	10
SS:LS=50:50, r/c = 15%	50	0	50	15
RCA:LS=70:30, r/c = 0%	0	70	30	0
RCA:LS=70:30, r/c = 3%	0	70	30	3
RCA:LS=70:30, r/c = 5%	0	70	30	5
RCA:LS=70:30, r/c = 10%	0	70	30	10
RCA:LS=70:30, r/c = 15%	0	70	30	15
RCA:LS=50:50, r/c = 0%	0	50	50	0
RCA:LS=50:50, r/c = 3%	0	50	50	3
RCA:LS=50:50, r/c = 5%	0	50	50	5
RCA:LS=50:50, r/c = 10%	0	50	50	10
RCA:LS=50:50, r/c = 15%	0	50	50	15

*5% cement content by weight

4.2.3 Laboratory experimental program

The main laboratory program consisted of resilient modulus and fatigue tests on cylindrical samples by applying indirect tensile loads at a temperature of 25°C using an universal test machine (Figure 4.2).

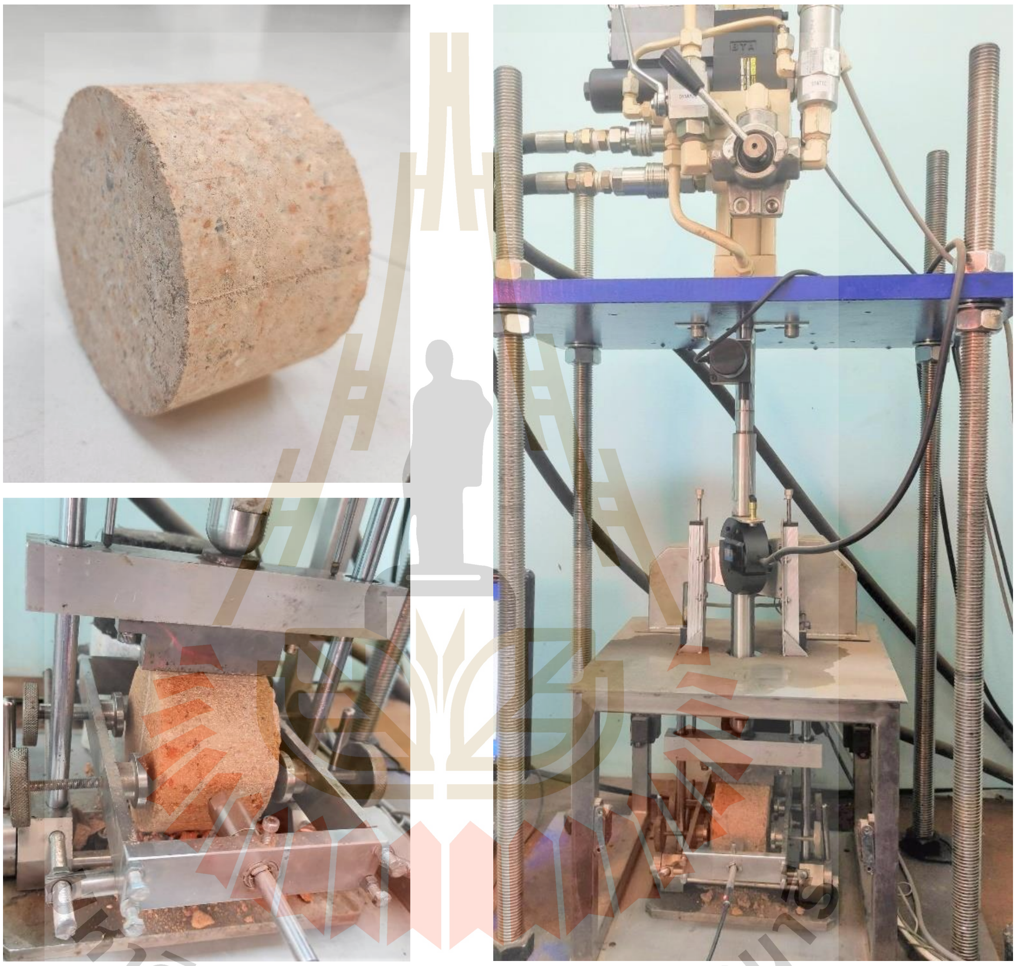


Figure 4.2 Photograph of cylindrical samples and testing equipment in this research

a. Indirect tensile resilient modulus (IT M_r)

IT M_r test is commonly performed based on ASTM D4123 (ASTM-D4123-82, 1995) to measure the relative quality of materials for pavement design and analysis. The test was carried out on cylindrical samples of 101.6 mm in diameter and 63.5 mm in height using UTM under the indirect tension mode. The applied load frequency is 1 Hz with a test duration of 0.1 s and a rest period of 0.9 s. Based on

ASTM D4123, the applied load range is from 10% to 50% of the ITS value, and a minimum of 50 to 200 load repetitions are recommended for determining the resilient modulus. In this research, 150 pulses of repetitions were determined at a stress level of 30% of ITS, as suggested by Fedrigo, Núñez, Castañeda López, Kleinert, and Ceratti (2018). The average of the last five values of elastic stiffness after the first 100 cycles is defined as IT M_r. Three samples of each mixture were tested under the same condition, and the average was presented as IT M_r, which was calculated based on the following equation:

$$IT\ M_r = \frac{P(v+0.27)}{t\Delta h} \quad (1)$$

where IT M_r is the indirect tensile resilient modulus (MPa), *P* is the repeated load (N), v is the Poisson's ratio (assumed to be 0.35), t is the sample thickness, and Δh is the total horizontal recoverable deformation (mm).

b. Indirect tensile fatigue (IT F_n)

Fatigue test is conducted to assess the fatigue resistance of cement-stabilized materials. Either controlled stress (load) or controlled strain (displacement) is used in the fatigue test. In the controlled stress fatigue testing, the applied stress is kept constant, and the strain gradually increases, which is suitable for lightly cement stabilized material. While a constant strain is kept constant for the controlled strain testing mode. In this study, an indirect tensile fatigue test is carried out in controlled stress mode by EN 12697 (BS-EN-12697-24, 2012).

In the BS EN 12697-24 standard, the fatigue life is defined as the total number of loading cycles needed to fail the sample. The tensile strain at the center of the sample is calculated with the equation:

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

where Poisson's ratio (v) is assumed as equal to 0.35, hence equation (2) becomes:

$$\varepsilon_0 = 2.1\frac{\Delta H}{d} \quad (3)$$

where ε_0 is the tensile strain at the center of the samples ($\mu\varepsilon$), ΔH is the measured horizontal deformation (mm), *d* is the sample diameter (mm), and the plastic tensile strain at the center of the sample is calculated with the following equation:

$$\varepsilon_p = 2.1\frac{\Delta p}{d} \quad (4)$$

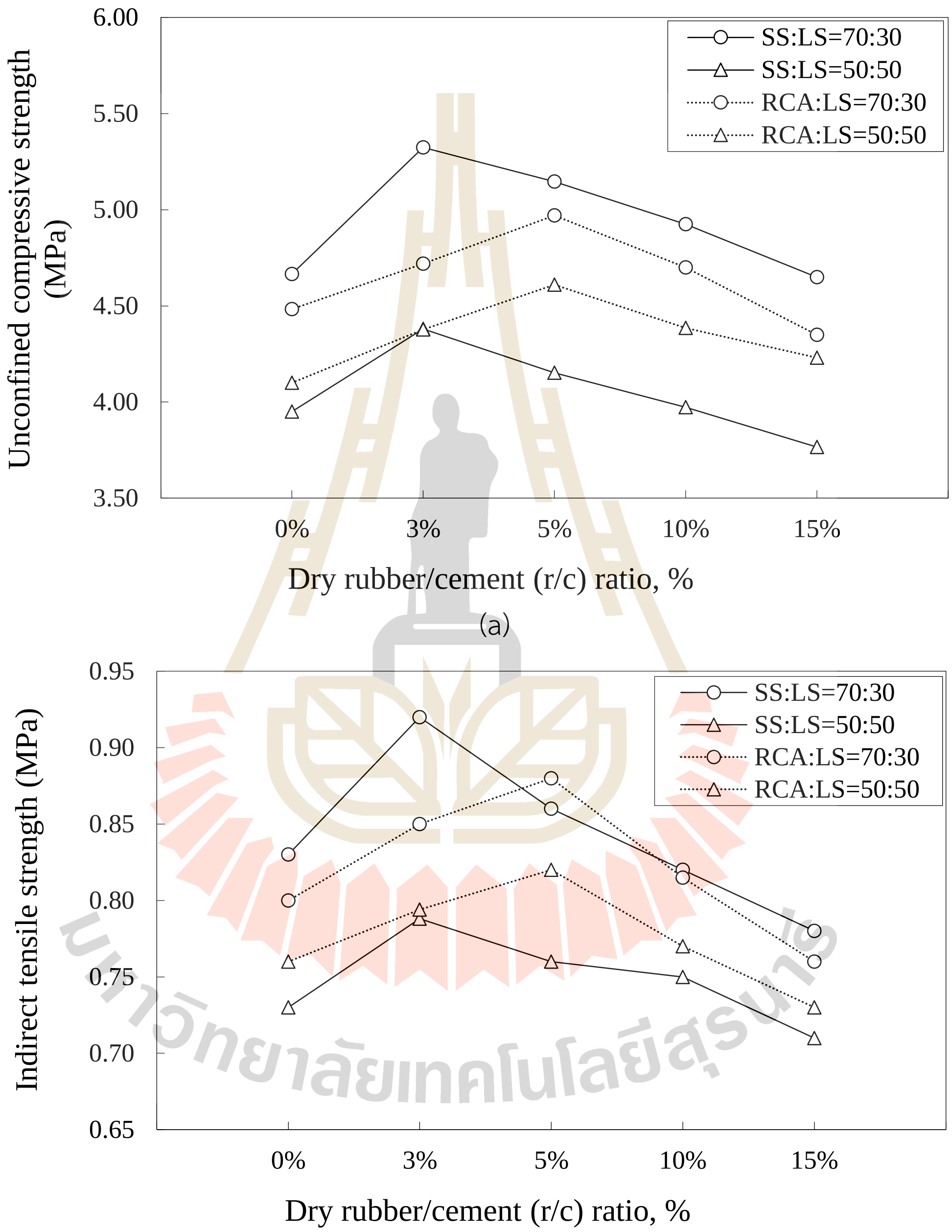
where ε_p is the tensile plastic strain at the center of the sample ($\mu\varepsilon$), and Δp is the initial plastic deformation (mm), and d is the sample diameter (mm).

4.3 Results and discussion

4.3.1 Mechanical strength

Figures 4.3a and 4.3b, respectively, illustrate the 28-day UCS and ITS of cement- and cement-NRL stabilized SS/RCA:LS blends at different SS/RCA:LS replacement ratios and dry rubber/cement (r/c) ratios. Figure 4.3a demonstrates that the highest UCS of cement-NRL stabilized SS:LS blends was found at an r/c ratio of 3% and was higher than that of cement-stabilized SS:LS blends at both SS:LS=70:30 and SS:LS=50:50. While the r/c ratio of 5% was found to provide the highest UCS of cement-NRL stabilized RCA:LS blends and higher than the cement-stabilized RCA:LS blends at both RCA:LS=70:30 and RCA:LS=50:50. As such, the r/c ratios of 3% and 5% were considered as the optimum r/c ratios for cement-NRL stabilized SS:LS and RCA:LS blends. For both SS:LS and RCA:LS blends, the cement-NRL stabilized samples contained higher recycled material replacement ratio indicated higher UCS values at a particular r/c ratio. This might be because both recycled materials (SS and RCA) had better mechanical properties than LS. For instance, SS had a higher resistance to Los Angeles abrasion than RCA and LS, respectively.

The trends of ITS results of cement-NRL stabilized SS:LS blends and RCA:LS blends were noticeably similar to those of UCS results. This indicates that the additional NRL can improve both compressive and tensile strengths of cement-stabilized SS/RCA:LS blends, which provide advantages for using these bound materials as a pavement base course. Farhan et al. (2015) proved that the high tensile strength of cement-stabilized material could improve pavement service life as it mitigates the fatigue cracking of the asphalt surface, which is a significant cause of pavement failure. A microstructural analysis using scanning electron microscope from the previous authors' research indicated that at the optimum r/c ratio, the NRL polymer films could enhance the interparticle bonding of cement-stabilized recycled material (Tran et al., 2022), which is similar to the other research on cement-NRL stabilized soil material (2020; Buritatum et al., 2022a; Jose & Kasthurba, 2020). On the other hand, the excessive NRL used in cement-stabilized materials exbibits a negative effect on its microstructural properties as the thick NRL films retard the cement hydration, resulting in the low mechanical strength of cement-NRL stabilized materials.



(b)

Figure 4.3 (a) Unconfined compressive strength, and (b) Indirect tensile strength of 28-day cement- and cement-NRL stabilized SS:LS and RCA:LS samples at different SS/RCA:LS replacements and dry rubber/cement (r/c) ratios.

4.3.2 Indirect tensile resilient modulus (IT Mr)

Figure 4.4 summarizes the IT M_r values of cement- and cement-NRL stabilized SS:LS and RCA:LS blends at different SS/RCA replacement ratios and various r/c ratios. Similar to UCS and ITS results, the IT M_r of cement-NRL stabilized SS:LS and RCA:LS blends at both SS/RCA:LS replacement ratios increased with an increase of r/c ratio until the highest values at the optimum r/c ratios and then decreased. The highest IT M_r values of cement-NRL stabilized SS:LS blends and RCA:LS blends were found at the optimum r/c ratios of 3% and 5%, respectively, which were higher than those of cement-stabilized SS:LS and RCA:LS blends. The IT M_r values of cement-NRL stabilized SS:LS=70:30 and SS:LS=50:50 samples at optimum r/c ratio = 3% were 20% and 24% higher than those of cement-stabilized SS:LS=70:30 and SS:LS=50:50 samples, respectively. While the IT M_r values of cement-NRL RCA:LS=70:30 and RCA:LS=50:50 samples at optimum r/c ratio = 5% were increased by 17% and 22% compared with those of cement-stabilized RCA:LS=70:30 and RCA:LS=50:50 samples, respectively. It implied that the NRL additive enhanced mechanical strength and cyclic stiffness properties.

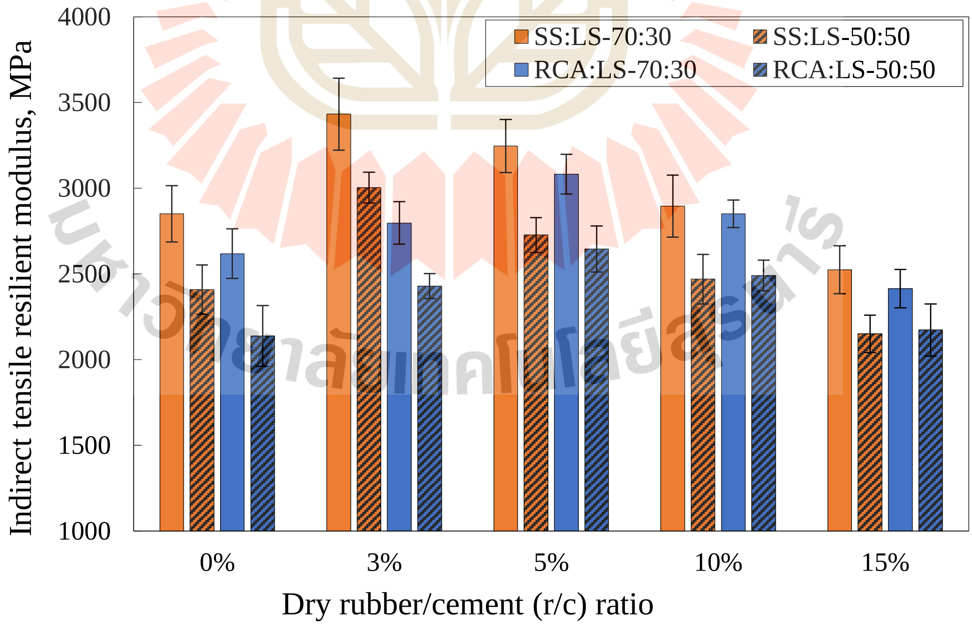


Figure 4.4 Indirect tensile resilient modulus of cement- and cement-NRL stabilized SS:LS and RCA:LS blends at different SS/RCA replacements and dry rubber/cement (r/c) ratios.

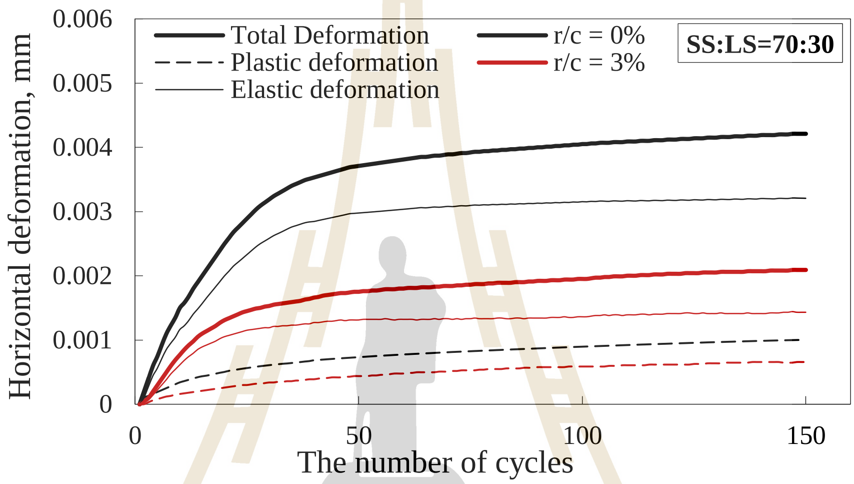
For a particular type of recycled material, the samples with 70% of recycled material replacements (SS:LS=70:30 and RCA:LS=70:30) had higher IT M_r values than those with 50% recycled material replacements (SS:LS=50:50 and RCA:LS=50:50) at the same r/c ratio. Furthermore, at the optimum r/c ratio, cement-NRL stabilized SS:LS blends exhibited higher IT M_r values than cement-NRL stabilized RCA:LS blends. This can be attributed to the mechanical and physical properties of SS were superior to those of RCA and LS, respectively. For instance, SS had LA abrasion = 17.2%, CBR = 58%, and flakiness index = 3.20, RCA had LA abrasion = 31%, CBR = 43%, and flakiness index = 8.92, while LS had LA abrasion = 34%, and CBR = 18%. From the previous similar research, the mechanical and physical properties of the materials were found to influence the resilient modulus of cement-stabilized recycled waste materials (Arulrajah et al., 2020; Disfani et al., 2014).

Following local and international road authorities such as AUSTROADS and ASSHTO guidelines for mechanistic-empirical pavement design, the pavement structure layers were evaluated by the resilient modulus (AASHTO, 2015; Elliott & Thornton, 1988; Jameson, 2008). Resilient modulus is a vital pavement design parameter (measurement indicator) of a material’s deflection characteristic; the design thickness depends on the resilient modulus. In addition, pavement service life is significantly related to distress failures, including fatigue cracking and rutting mechanism of pavement structures. In order words, the high resilient modulus of the cement-NRL stabilized base layers can enhance the resistance against the fatigue cracking and rutting failure of the pavement under cyclic loading. NRL additive can enhance the resilient modulus of cement-stabilized SS/RCA:LS blends, which means the pavement service life might be extended when used these materials in the pavement structures.

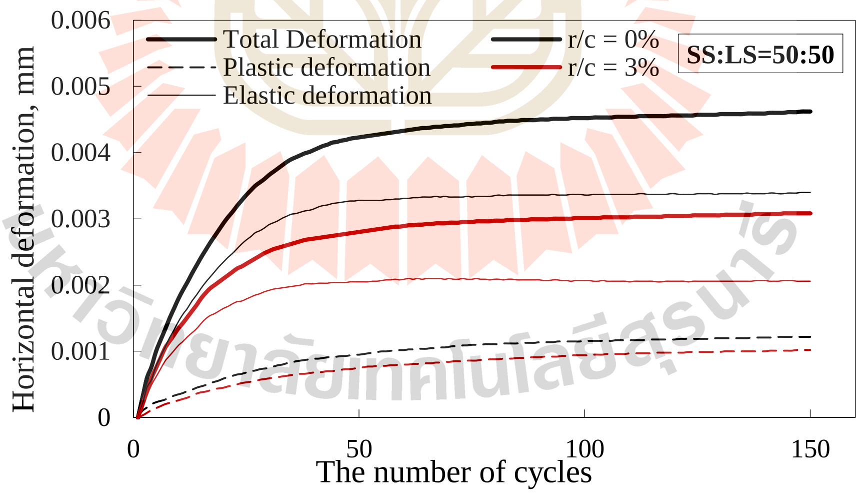
Resilient modulus is a critical mechanistic property of a material described from a stress-strain relationship, which is similar in concept to the modulus of elasticity. However, the difference is that the modulus of elasticity is determined from the static load (general stress-strain relationship). In contrast, the resilient modulus is determined from the cyclic load (cyclic stress-strain relationship). Hence, the resilient modulus is defined as the stress amplitude (applied load per area of the specimen) proportional to strain amplitude (recoverable deformation compared to its original height). Based on the cyclic stress-strain relationship, the stress and strain increase as the load is applied. However, when the stress is reduced, the strain also reduces, but not all strain is recovered after the stress is removed. In other words, the total horizontal deformation is the sum of elastic deformation or recoverable deformation (resilient behavior) and plastic deformation or permanent deformation (absorbing behavior).

Since the pavement's service life is significantly associated with the pavement structure deformation, the horizontal deformations versus the number of cycles behaviors of cement- and cement-NRL stabilized SS/RCA:LS blends were examined in this research. Figure 4.5 demonstrates the relationship between horizontal deformations and the number of cycles under load repetitions at 30% stress level of cement- and cement-NRL stabilized 70SS:30LS, 50SS:50SS, 70RCA:30LS, and 50RCA:50LS samples at optimum r/c ratios. It is of interest to demonstrate that the horizontal deformations versus the number of cycles relationship of cement- and cement-NRL stabilized SS:LS blends and RCA:LS blends at all recycled material replacement ratios were similar. The NRL additive significantly reduced the horizontal deformations (total, elastic, and plastic deformations) of cement stabilized SS/RCA:LS blends.

Several researchers found that the density increase could enhance the resistance to permanent deformation of materials under repetitive loading. Elliott and Thornton (1988) and Hall et al. (2001) reported that the density of the granular base materials notably influenced the resilient modulus, and the high density could significantly reduce the plastic strain (permanent deformation). The samples under 95% compaction effort exhibited remarkably large permanent axial strain when compared with the samples under 100% compaction (Barksdale, 1972). Allen (1973) also reported that the plastic strain of the compacted crushed limestone and gravel aggregate under the Proctor energy was respectively reduced by approximately 80% and 20% when they were subjected to the modified Proctor energy. In this study, the cement-NRL stabilized SS:LS and RCA:LS blends at optimum r/c ratio had a higher density than cement-stabilized SS:LS and RCA:LS blends at the same compaction energy. The NRL films can enhance the interparticle bonding of the compacted cement-stabilized SS/RCA:LS blends and the mechanical strength (UCS and ITS) properties, which lead to the improvement of resilient modulus. The high resilient modulus and low permanent deformation of cement-NRL stabilized SS/RCA:LS blends are associated with the improvement of the pavement structure capacity against fatigue rutting failure. As such, the pavement life might last longer as similar to the study on the cement-NRL stabilized soil (Udomchai et al., 2021).

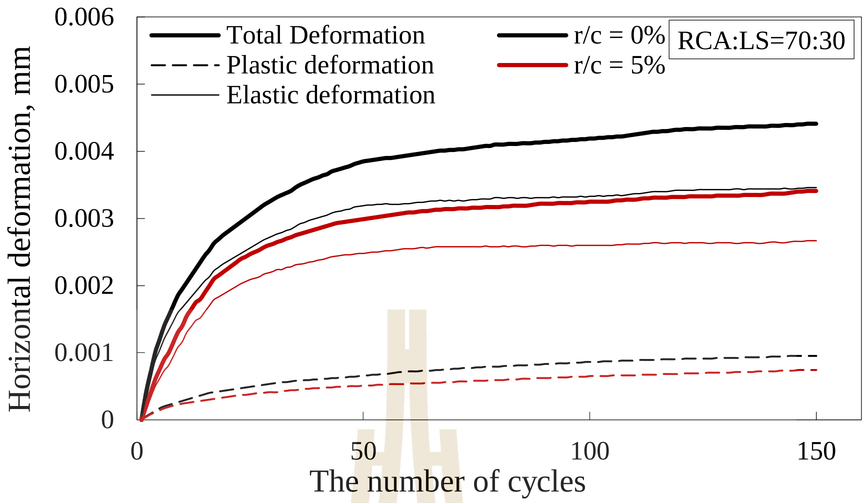


(a)

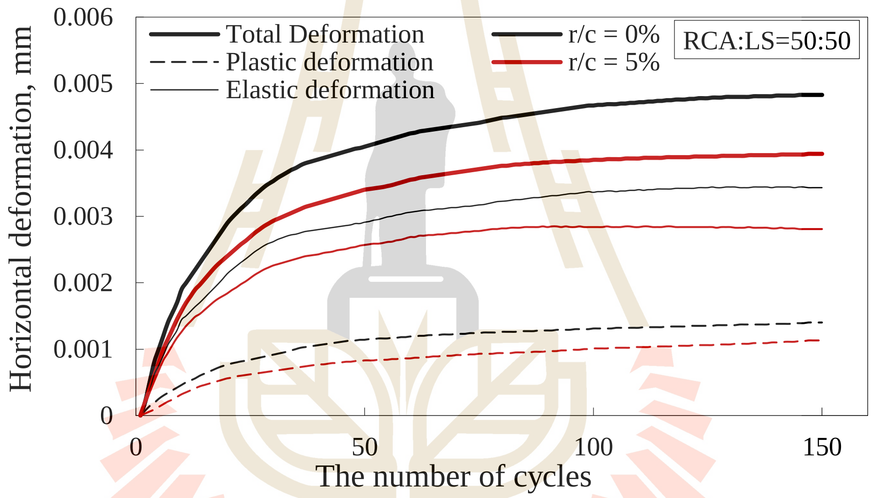


(b)

Figure 4.5 Relationship between horizontal deformations and the number of cycles under repeated-load at 30% stress level of cement- and cement-NRL stabilized SS/RCA:LS blends at optimum r/c ratio: (a) SS:LS=70:30, (b) SS:LS=50:50



(c)



(d)

Figure 4.5 (Continued) Relationship between horizontal deformations and the number of cycles under repeated-load at 30% stress level of cement- and cement-NRL stabilized SS/RCA:LS blends at optimum r/c ratio: (c) RCA:LS=70:30, and (d) RCA:LS=50:50.

4.3.3 Indirect tensile fatigue life

The typical relationship between the number of cycles and the deformation of a sample under cyclic loading is divided into three zones (Figure 4.6). The first zone expresses the rapid development rate of deformation with a small number of cyclic loadings; the second zone represents the gradual development of deformation with the linear increase of the number of cycles. The accumulated micro-cracks are formed and gradually developed during the first and the second zones, leading to the sudden failure of the sample in the third zone (Kavussi & Modarres, 2010; Modarres & Bengar, 2017). Following EN 12697 (BS-EN-12697-24, 2012), indirect tensile fatigue life (ITFL) is defined as the number of cycles (F_n) at the fracture point of the sample under the cyclic load test.

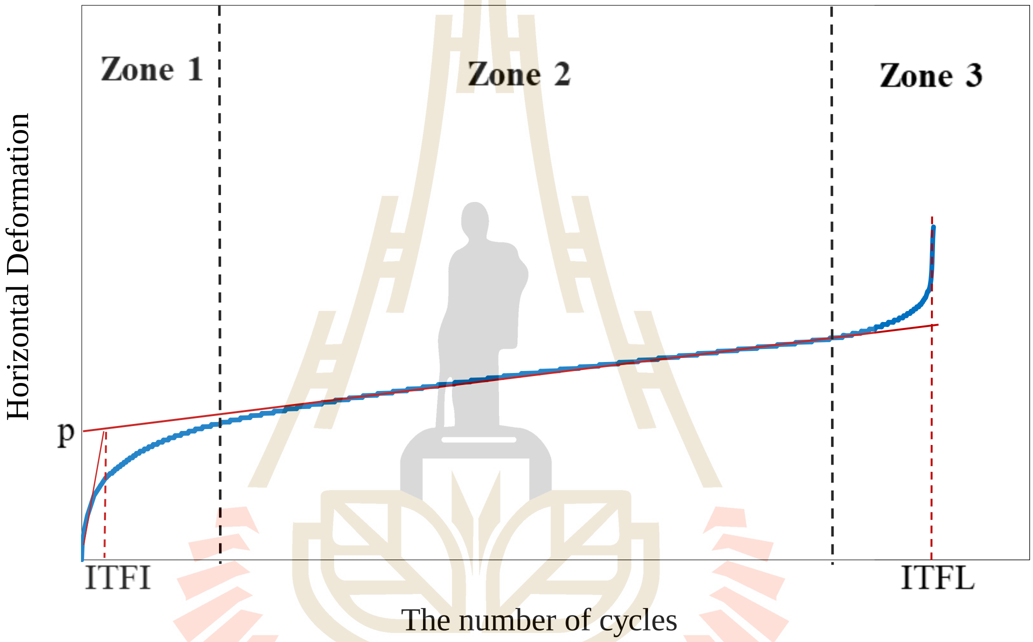
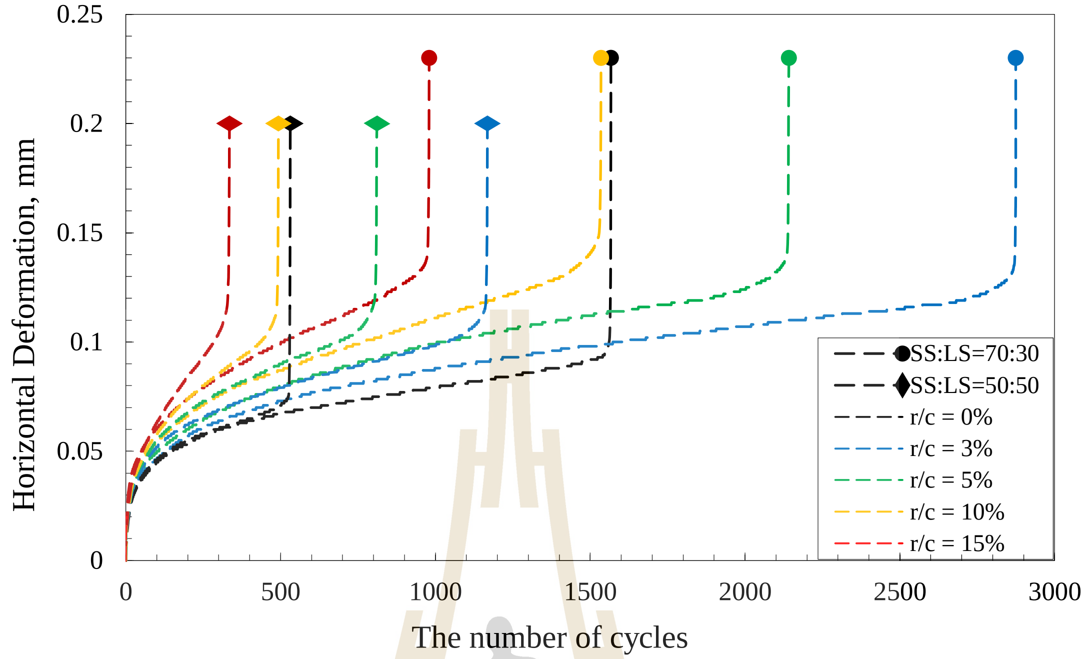


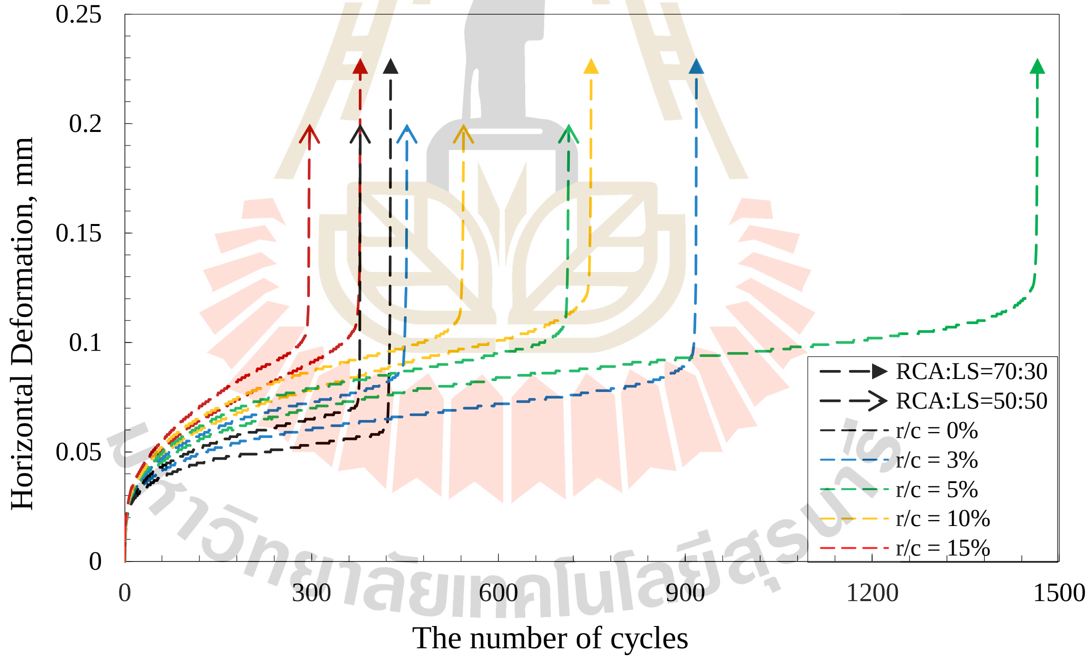
Figure 4.6. The schematic plot of the relationship between horizontal deformation and the number of cycles.

Figure 4.7 illustrates the relationship between the number of cycles and horizontal deformation under the fatigue test at 70% stress level of cement- and cement-NRL stabilized SS:LS and RCA:LS blends at different r/c ratios. Furthermore, Figure 4.8 summaries the fatigue life of cement- and cement-NRL stabilized SS:LS and RCA:LS blends at different recycled material replacement ratios and different r/c ratios. For a particular type of recycled material, the fatigue life results were consistent with the resilient modulus results in that the cement-NRL stabilized SS:LS blends at an optimum ratio of 3% and RCA:LS blends at an optimum ratio of 5% indicated the highest fatigue life. At the optimum r/c ratios, the cement-NRL stabilized SS/RCA:LS blends had fatigue life about 2 to 3 times higher than the cement-stabilized SS/RCA:LS blends. It implies that the NRL additive can improve the resilient modulus and enhance the fatigue life of the cement-NRL stabilized SS/RCA:LS blends under repeated loading. This might be attributed to the cement and blended materials matrix formed during the hydration process was reinforced by the NRL film formation, resulting in the strength development (Muhammad & Ismail, 2012). In addition, Tran et al. (2022) indicated that the NRL films could also fill the pore spaces between the cement and blended materials matrix, leading to bonding strength enhancement and porosity reduction. This is in agreement with the research conducted on the cement-treated sand by Festugato et al. (2021), in that the resilient modulus and fatigue life increased with the decrease of porosity of cement stabilized materials. However, beyond the optimum r/c ratio, the cyclic properties of cement-NRL stabilized materials were reduced as the excessive amount of NRL retards the cement hydration process; hence the decrease of cement hydration products (C-S-H) is (Buritatum et al., 2022a; Tran et al., 2022).

Meanwhile, the cement-NRL stabilized SS:LS blends had higher fatigue life than the cement-NRL stabilized RCA:LS blends at the same replacement ratio and r/c ratio. For cement-stabilized SS:LS and RCA:LS blends, the fatigue life of SS:LS=70:30, SS:LS=50:50, RCA:LS=70:30, and RCA:LS=50:50 reached 1567, 531, 425, and 378 cycles, respectively. At an optimum r/c ratio of 3%, the cement-NRL stabilized SS:LS=70:30 and SS:LS=50:50 had a fatigue life of 2865 and 1168 cycles, respectively. At an optimum r/c ratio of 5%, the cement-NRL stabilized RCA:LS=70:30 and RCA:LS=50:50 had a fatigue life of 1465 and 714 cycles, respectively. Besides the influence of NRL additive, the engineering and physical properties of aggregates might influence the mechanical strength (UCS and ITS) and the resistance to the fatigue loading of cement-NRL stabilized SS:LS and RCA:LS blends. The resistance to Los Angle abrasion, CBR, and flakiness index of SS were superior to those of RCA, and LS, respectively in this study, which is also similar to the previous finding (Sudla et al., 2018; Tran et al., 2022). As a result, the cement-NRL stabilized SS/RCA:LS blends with 70% recycled material replacement ratio indicated high fatigue life than the samples with 50% recycled material replacement ratio.



(a)



(b)

Figure 4.7 Relationship between the number of cycles and horizontal deformation under fatigue test at 70% stress level: (a) cement- and cement-NRL stabilized SS:LS blends, (b) cement- and cement-NRL stabilized RCA:LS blends at different r/c ratios.

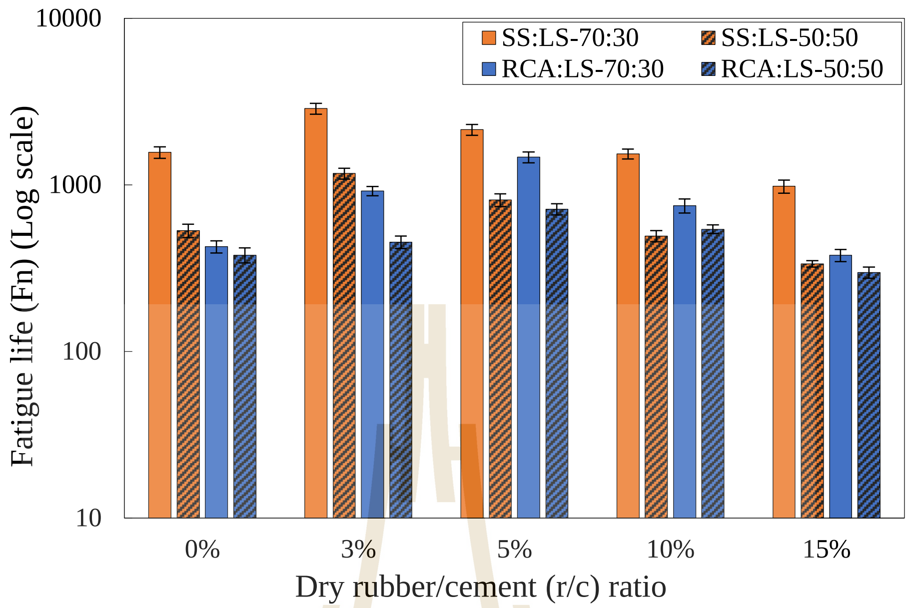
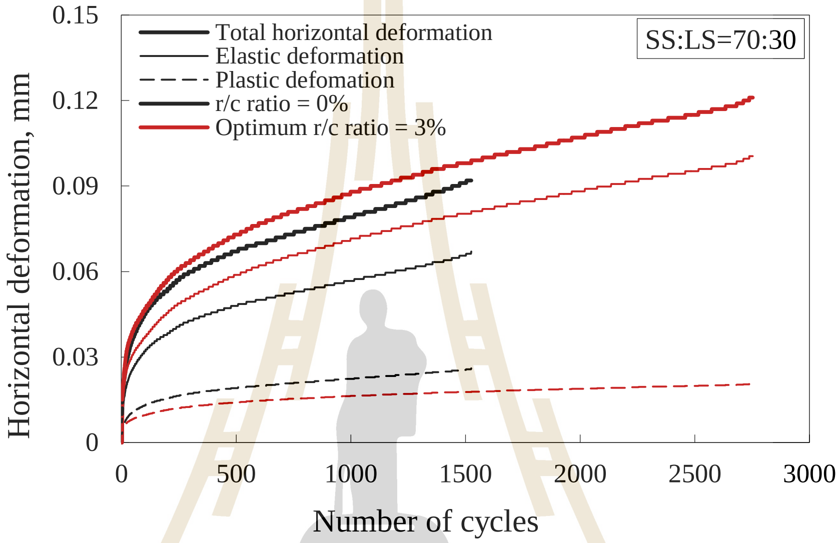
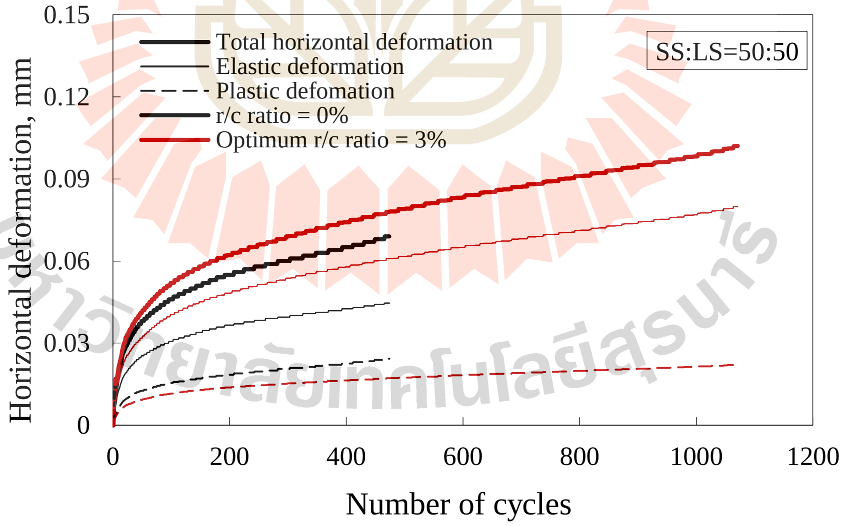


Figure 4.8 Fatigue life (Fn) of cement- and cement-NRL stabilized SS:LS and RCA:LS blends at different SS/RCA replacements and r/c ratios.

Figure 4.9 demonstrates the relationship between the number of cycles and horizontal deformations of cement-stabilized SS/RCA:LS blends and cement-NRL stabilized SS:LS blends at an optimum ratio of 3% and RCA:LS blends at an optimum ratio of 5% under cyclic loading at 70% stress level. It is interesting to note that the total horizontal deformations of cement-NRL stabilized SS/RCA:LS blends at both 70% and 50% recycled material replacement ratios were higher than cement-stabilized SS/RCA:LS blends at 70% stress level. It is different from the results shown in Figure 4.5 in that the total deformations of cement-NRL stabilized SS/RCA:LS blends at both 70% and 50% recycled material replacement ratios at 30% stress level were lower than those of cement-stabilized SS/RCA:LS blends at 30% stress level. However, the plastic deformations of cement-NRL stabilized SS/RCA:LS blends at optimum r/c ratios with all recycled material replacement ratios were lower than those of cement-NRL stabilized SS/RCA:LS blends under both 30% and 70% stress levels. Gnanendran and Piratheepan (2008) reported a similar degree of plastic deformation of the cement-stabilized soil at a 50% - 75% stress level. The accumulated plastic deformation in granular-based and subbase layers was found to be one of the most important causes of severe rutting development at the pavement surface and led to the failure of pavement serviceability under cyclic traffic load (Khedr, 1985; Mohammad, Puppala, & Alavilli, 1994; Vollmert, 2021). This confirmed that the NRL additive crucially contributed to the improvement of fatigue life and reduced the permanent deformation of cement-stabilized recycled materials as a pavement base course under repeated traffic load.

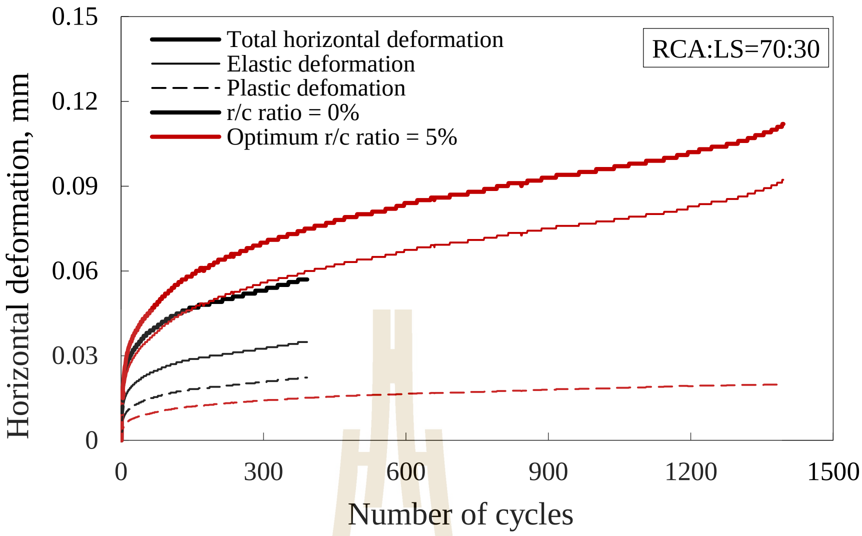


(a)

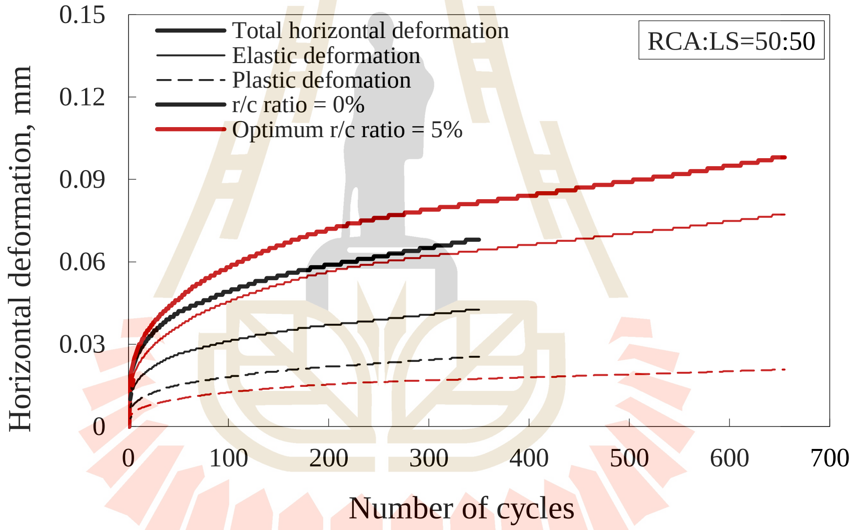


(b)

Figure 4.9 Relationship between horizontal deformations and the number of cycles under repeated-load at 70% stress level of cement- and cement-NRL stabilized SS/RCA:LS blends at optimum r/c ratio: (a) SS:LS=70:30, (b) SS:LS=50:50.



(c)



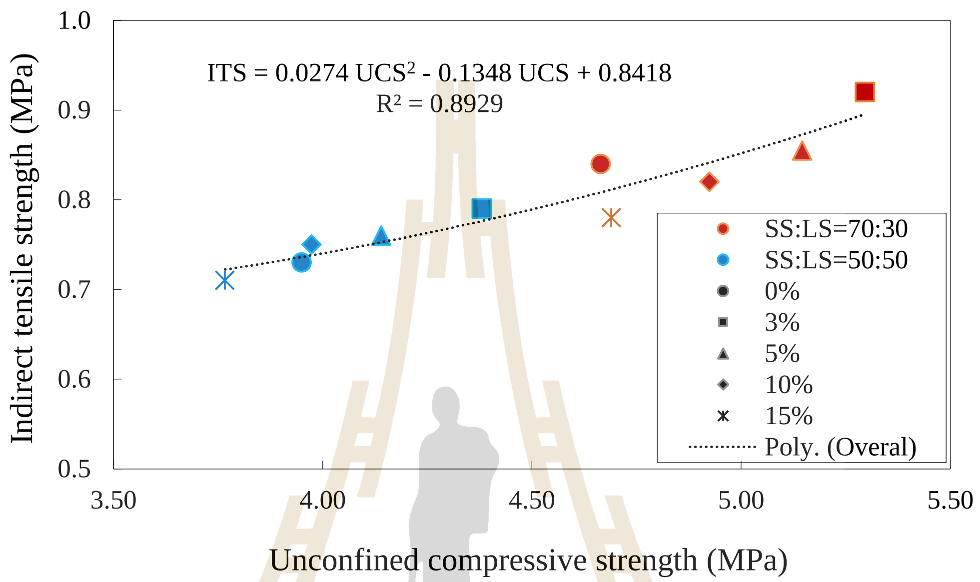
(d)

Figure 4.9 (Continued) Relationship between horizontal deformations and the number of cycles under repeated-load at 70% stress level of cement- and cement-NRL stabilized SS/RCA:LS blends at optimum r/c ratio: (c) RCA:LS=70:30, and (d) RCA:LS=50:50.

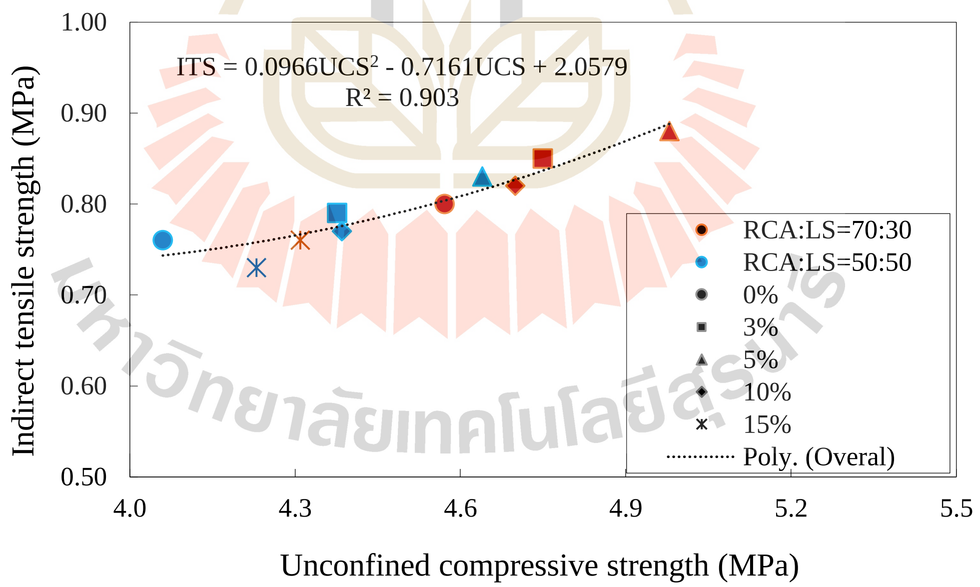
In addition, the relationship between the number of cycles and horizontal deformations in Figure 4.9 clearly indicated the sudden failure of cement-stabilized SS/RCA:LS blends at all recycled material replacement ratios, demonstrating the brittle behavior when compared with that samples with additional NRL additive. It implies that the additional NRL polymer additive can improve the ductility behavior of cement-stabilized recycled materials. Vo and Plank (2018) reported that the NRL films are a bridge to transfer the tensile stress to the particles and prevent sudden failure. The positive role of NRL in improving the brittle behavior of cement-stabilized SS:LS and RCA:LS under compressive loading was also proved in the previous study, in which the failure strain of cement-NRL stabilized samples increased with an increase of r/c ratio (Tran et al., 2022).

4.3.4 Permanent deformation and fatigue model

In general, permanent deformation is one of the essential types of repeated load-associated distresses (fatigue cracking and rutting) occurring in the pavement structure. The pavement designers and engineers concern about fatigue cracking and rutting effect on the lateral and longitudinal profiles at the pavement surface. This distress failure can reduce the pavement's service life and significant safety pavement user's concern. The pavement deformation is associated with rutting and fatigue cracks gradually developing with accumulated load repetitions. In addition, the variation of rut depth is a crucial factor affecting road roughness and serviceability. In recent years, the M-E pavement design guide has become a state-of-the-practice approach for designing and analyzing pavement structures based on the mechanistic-empirical principles. This is because of M-E approaches determined the pavement responses, including stress, strains, and deformations, and applied those responses to determine the accumulated damage over time under the repeated load. Hence, many researchers carried out fatigue tests to evaluate the fatigue properties of the unbound and bound materials, including cement-stabilized lateritic soil and cement-stabilized granular and recycled aggregates (Biswal, Sahoo, & Dash, 2020a; Disfani et al., 2014; Jitsangiam et al., 2016b; Paul & Gnanendran, 2016; Paul et al., 2015). However, no study was found on fatigue characteristics of cement-NRL stabilized recycled materials, which is the important objective of this research. The fatigue properties test conducted to determine the resilient modulus, fatigue life, and permanent deformation is incredibly time-consuming and complicated to perform, resulting in a lack of a prediction model for implementation. Therefore, this research proposed those fatigue properties associated with the conventional strength properties of the cement- and cement-NRL stabilized SS:LS and RCA:LS blends as sustainable pavement base materials. The following steps are involved in selecting the fatigue properties of the studied materials.



(a)

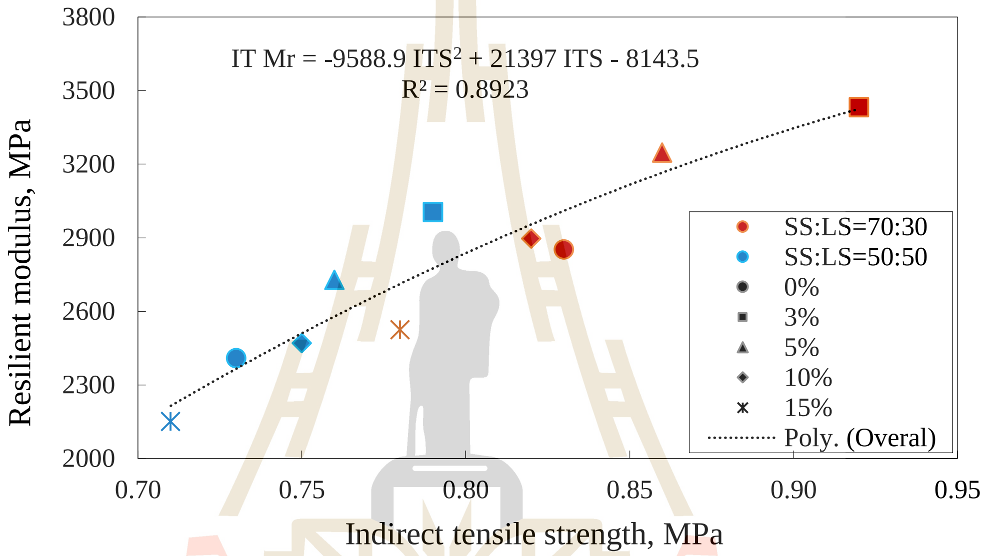


(b)

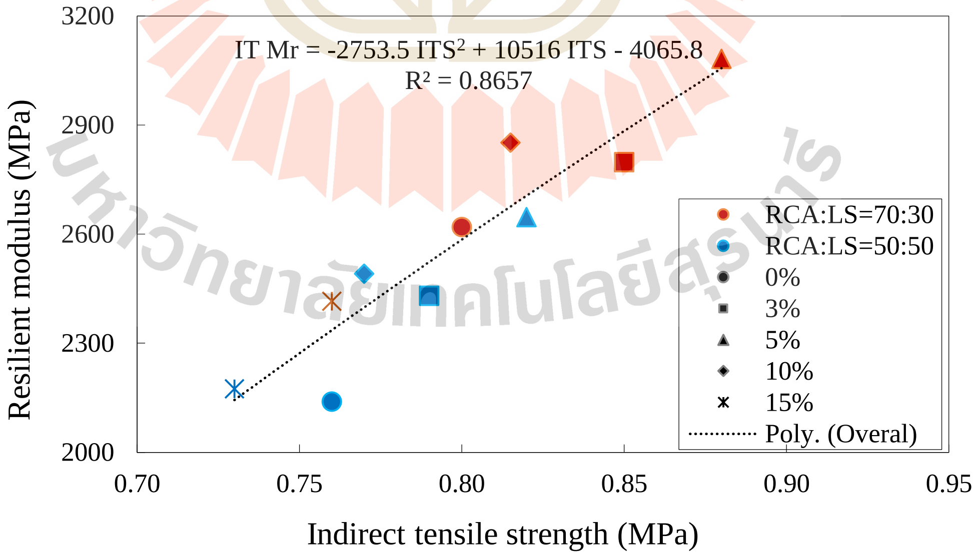
Figure 4.10 Relationship between UCS and ITS of SS:LS (a) and RCA:LS (b) samples at different r/c ratios.

Step 1. Develop a relationship between UCS and ITS of cement- and cement-NRL stabilized SS:LS and RCA:LS blends at different recycled replacement ratios and r/c ratios (Figure 4.10).

Step 2. The resilient modulus was performed based on the indirect tensile test. Hence, it is easy to determine the resilient modulus of the studied materials based on the resilient modulus versus ITS relationship as shown in Figure 4.11.



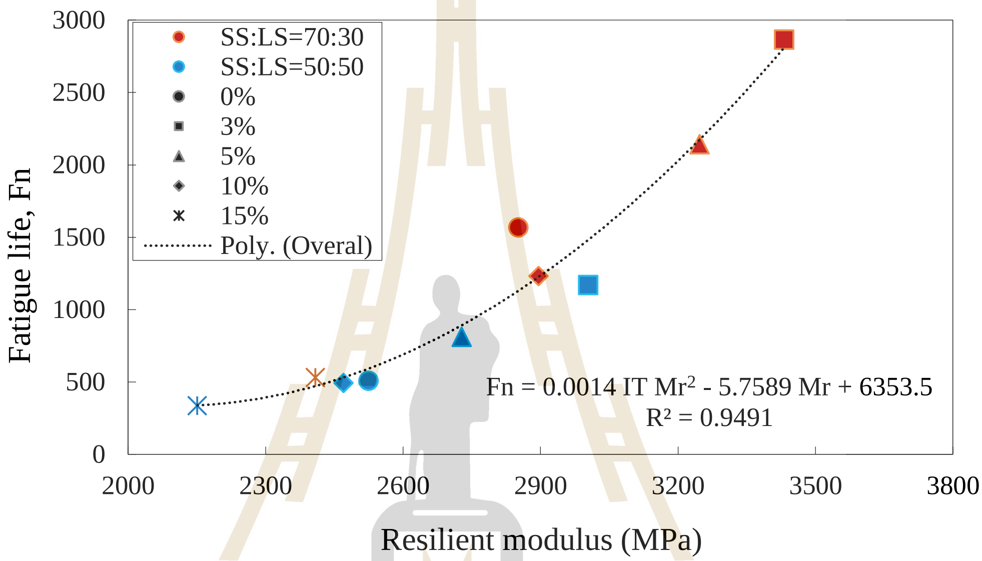
(a)



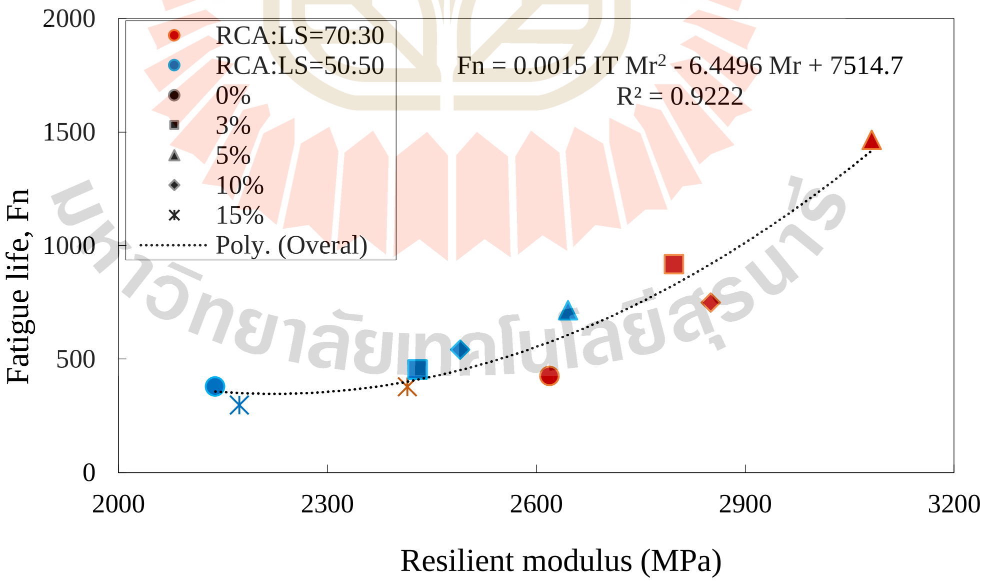
(b)

Figure 4.11 Relationship between ITS and IT M_r of SS:LS (a) and RCA:LS (b) samples at different r/c ratios.

Step 3. Similar to the determination procedure of resilient modulus, the fatigue life of the studied materials was performed based on the indirect tensile test under cyclic load conditions. The predicted fatigue life of the studied materials can be determined from a relationship between fatigue life and resilient modulus, as depicted in Figure 4.12.



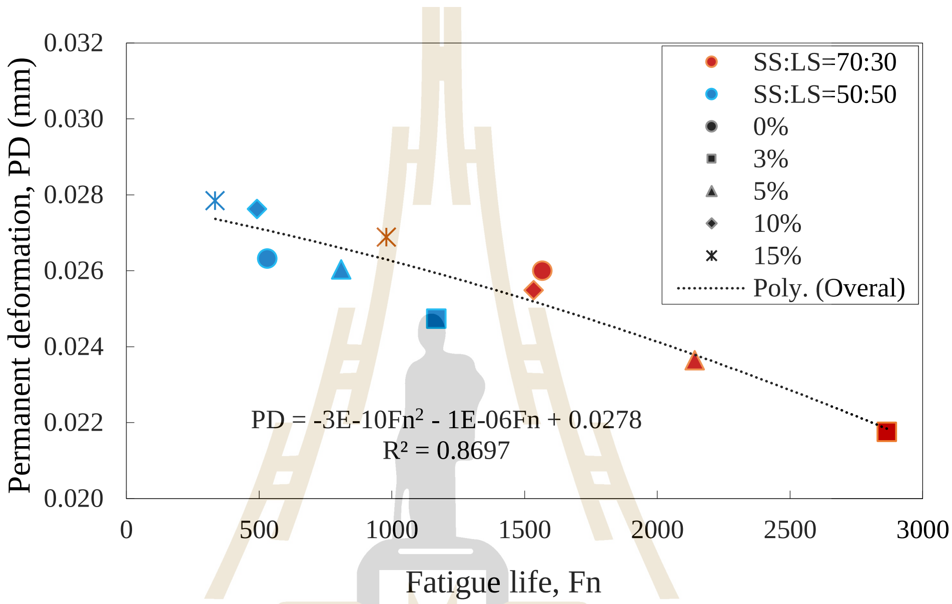
(a)



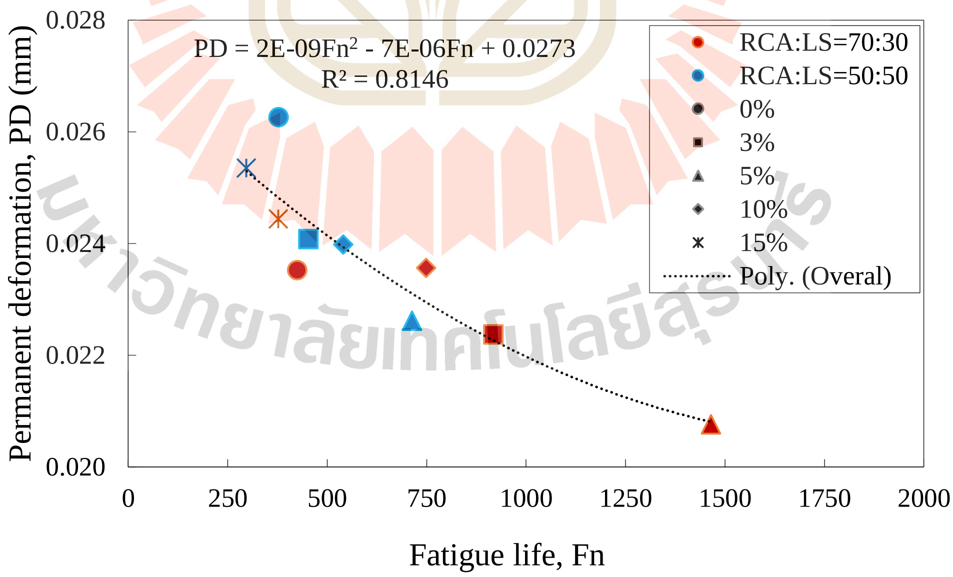
(b)

Figure 4.12 Relationship between IT M_r and Fatigue life of SS:LS (a) and RCA:LS (b) samples at different r/c ratios.

Step 4. Develop a relationship between permanent deformation and fatigue life of the studied materials (Figure 4.13). Based on this relationship, the permanent deformation of the studied materials is estimated to be associated with the number of cycles. In other ways, the permanent deformation model can predict the rutting distress in the pavement base layer.



(a)



(b)

Figure 4.13 Relationship between Fatigue life and Permanent deformation of SS:LS (a) and RCA:LS (b) samples at different r/c ratios.

4.4 Conclusions

This research investigated the influence of NRL additive on the resilient modulus and fatigue properties of cement-stabilized lateritic soil with recycled materials (SS and RCA) replacements. Four blends included SS:LS=70:30, SS:LS=50:50, RCA:LS=70:30, and RCA:LS=50:50, and 5% cement content by weight were designed for this research. To investigate the influence of NRL additive on cement-stabilized SS/RCA:LS blends, the dry NRL to cement (r/c) were designed to be 0%, 3%, 5%, 10%, and 15%. The mechanical strength properties (UCS and ITS) and the fatigue properties including indirect tensile resilient modulus (IT M_r) and fatigue life of the studied materials under indirect tensile force were investigated. The following conclusions can be drawn:

1. The r/c ratios of 3% and 5% were found to be the optimum r/c ratio for cement-NRL stabilized SS:LS blends and RCA:LS blends, respectively that produce the highest UCS, ITS, IT M_r, and fatigue life, which were higher than those of cement-stabilized SS:LS blends and RCA:LS blends for all recycled material replacement ratios. This is because the cement-blended materials matrix formed during the hydration process was reinforced by NRL film formation, resulted in a dense matrix and strength development. However, beyond the optimum r/c ratio, the excessive amount of NRL generated thick NRL films and retarded the cement hydration products, resulting in low-strength development.
2. Overall, the cement-NRL stabilized SS:LS blends exhibited higher mechanical strength properties and fatigue properties than the cement-NRL stabilized RCA:LS blends. In addition, for both types of recycled materials, the cement-NRL stabilized SS/RCA:LS blends contained 70% recycled material replacement ratio exhibited superior mechanical strength and fatigue properties than the samples contained 50% recycled material replacement ratio. This is attributed to SS having higher mechanical and physical properties including LA abrasion, CBR, and flakiness index than RCA and LS, respectively. It implied that besides the effluence of NRL additive, the good mechanical and physical properties of

aggregates attribute to the mechanistic and fatigue properties of cement-NRL stabilized soil with recycled material replacement ratios.

3. The relationship between the number of cycles and horizontal deformations under indirect tensile load repetitions demonstrated that the cement-stabilized SS/RCA:LS blends exhibited brittle behavior and the sudden failure occurred at the low number of cycles. The additional NRL additive can improve the ductility of cement-stabilized SS/RCA:LS blends. At the optimum r/c ratios, the cement-NRL stabilized SS/RCA:LS blends had higher fatigue life and lower permanent deformation (permanent deformation) at both 30% and 70% stress levels. The NRL additive can lubricate the compacted particles and increase the density and lower permanent deformation. Furthermore, the NRL films act as the bridge to transfer the tensile stress to particles and prevent the sudden failure of cement-NRL stabilized SS/RCA:LS blends.

The research outputs confirmed that NRL additive could improve the mechanistic and fatigue properties cement-stabilized soil with recycled material replacements, which enhance the service of the pavements under cyclic traffic loads. The mechanistic and fatigue models of cement- and cement-NRL stabilized soil with recycled material replacements are proposed and they are important for the pavement designers and engineers when using mechanistic-empirical (M-E) pavement design approach. Furthermore, it is found to be useful as the essential parameter for numerical modeling in M-E models. A numerical analysis based on the present experiment results is recommended for future study to develop the distress model, to predict the fatigue cracking life of the pavement structure when using cement-NRL stabilized recycled aggregates as the base materials.

4.5 References

AASHTO. (2015). Mechanistic-Empirical pavement design guide: A manual of practice. *American Association of State Highway and Transportation Officials*.

Agrela, F., Barbudo, A., Ramírez, A., Ayuso, J., Carvajal, M. D., & Jiménez, J. R. (2012). Construction of road sections using mixed recycled aggregates treated with cement in Malaga, Spain. *Resources, Conservation and Recycling, 58*, 98-106. Doi: 10.1016/j.resconrec.2011.11.003

Allen, J. (1973). The Effect of Non-Constant Lateral Pressures of the Resilient Response of Granular Materials. *Ph.D. dissertation. Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois*.

Arora, S., & Aydilek, A. H. (2005). Class F Fly-Ash-Amended Soils as Highway Base Materials. *Journal of Materials in Civil Engineering, 17*, 640-649. Doi: 10.1061/(ASCE)0899-1561(2005)17:6(640)

Arulrajah, A., Perera, S., Wong, Y. C., Horpibulsuk, S., & Maghool, F. (2020). Stiffness and flexural strength evaluation of cement stabilized PET blends with demolition wastes. *Construction and Building Materials, 239*. Doi: 10.1016/j.conbuildmat.2019.117819

ASTM-D1557-12. (2012). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3 (2,700 kN-m/m^3)). *West Conshohocken, PA: ASTM.* Doi: 10.1520/D1557-12

ASTM-D4123-82. (1995). Indirect Tension test for Resilient Modulus of Bituminous Mixtures. *West Conshohocken, PA: ASTM.*

Baghini, M. S., Ismail, A., & Karim, M. R. B. (2015). Evaluation of cement-treated mixtures with slow setting bitumenemulsion as base course material for road pavements. *Construction and Building Materials, 94*, 323-336. Doi: 10.1016/j.conbuildmat.2015.07.057

Baghini, M. S., Ismail, A., Naseralavi, S. S., & Firoozi, A. A. (2016). Performance evaluation of road base stabilized with styrene–butadiene copolymer latex and Portland cement. *International Journal of Pavement Research and Technology, 9*(4), 321-336. Doi: 10.1016/j.ijprt.2016.08.006

Barišić, I., Dimter, S., & Rukavina, T. (2015). Elastic properties of cement-stabilised mixes with steel slag. *International Journal of Pavement Engineering, 17*(9), 753-762. Doi: 10.1080/10298436.2015.1019496

Barksdale, R. D. (1972). Laboratory Evaluation of Rutting in Base Course Materials. *Proceedings of the 3rd International Conference on the Structural Design of Asphalt Pavements, 1*, 161-174.

Bhogal, B. S., Coupe, P. S., Davies, J., & Fendukly, L. M. (1995). Dynamic flexure tests of soil-cement beams. *Journal of materials science letters, 14*, 302-304.

Biswal, D. R., Sahoo, U. C., & Dash, S. R. (2020a). Fatigue Characteristics of Cement-Stabilized Granular Lateritic Soils. *Journal of Transportation Engineering, Part B: Pavements, 146*(1), 04019038. Doi: 10.1061/JPEODX.0000147

Biswal, D. R., Sahoo, U. C., & Dash, S. R. (2020b). Fatigue Characteristics of Cement-Stabilized Granular Lateritic Soils. *Journal of Transportation Engineering, Part B: Pavements, 146*(1). Doi: 10.1061/jpeodx.0000147

BS-EN-12697-24. (2012). Bituminous mixtures - Test methods for hot mix asphalt.

Bullen, F. (1994). The resilient moduli of cement treated materials. *Road & Transport Research, 3*.

Buritatum, A., Takaikaew, T., Horpibulsuk, S., Udomchai, A., Hoy, M., Vichitcholchai, N., & Arulrajah, A. (2020). Mechanical Strength Improvement of Cement-Stabilized Soil Using Natural Rubber Latex for Pavement Base Applications. *Materials in Civil Engineering, 32*(12). Doi: 10.1061/(ASCE)MT.1943-5533.0003471

Buritatun, A., Suddeepong, A., Horpibulsuk, S., Udomchai, A., Arulrajah, A., Mohammadinia, A., . . . Hoy, M. (2022a). Improvement of Tensile Properties of Cement-Stabilized Soil Using Natural Rubber Latex. *Journal of Materials in Civil Engineering, 34*(4). Doi: 10.1061/(ASCE)MT.1943-5533.0004173

Chakravarthi, S., Boyina, A., Singh, A. K., & Shankar, S. (2019). Evaluation of cement treated reclaimed asphalt pavement and recycled concrete pavement bases. *International Journal of Pavement Research and Technology, 12*(6), 581-588. Doi: 10.1007/s42947-019-0069-1

Christopher, B., Schwartz, C., & Boudreau, R. (2006). Geotechnical Aspects of Pavements Reference Manual. *Federal Highway Administration, Woodbury*.

Consoli, N. C., Marques, S. F. V., Floss, M. F., & Festugato, L. (2017). Broad-Spectrum Empirical Correlation Determining Tensile and Compressive Strength of

Cement-Bonded Clean Granular Soils. *Journal of Materials in Civil Engineering, 29*(6). Doi: 10.1061/(asce)mt.1943-5533.0001858

Disfani, M. M., Arulrajah, A., Haghighi, H., Mohammadinia, A., & Horpibulsuk, S. (2014). Flexural beam fatigue strength evaluation of crushed brick as a supplementary material in cement stabilized recycled concrete aggregates. *Construction and Building Materials, 68*, 667-676. Doi: 10.1016/j.conbuildmat.2014.07.007

Elliott, R. P., & Thornton, S. I. (1988). Resilient modulus and AASHTO pavement design. *Transportation Research Record*(1196).

Estabragh, A. R., Beytolahpour, I., & Javadi, A. A. (2011). Effect of Resin on the Strength of Soil-Cement Mixture. *Materials in Civil Engineering, 23*(7), 969-976. Doi: 10.1061/(ASCE)MT.1943-5533.0000252

Farhan, A. H., Dawson, A. R., Thom, N. H., Adam, S., & Smith, M. J. (2015). Flexural characteristics of rubberized cement-stabilized crushed aggregate for pavement structure. *Materials & Design, 88*, 897-905. Doi: 10.1016/j.matdes.2015.09.071

Fedrigo, W., Núñez, W. P., Castañeda López, M. A., Kleinert, T. R., & Ceratti, J. A. P. (2018). A study on the resilient modulus of cement-treated mixtures of RAP and aggregates using indirect tensile, triaxial and flexural tests. *Construction and Building Materials, 171*, 161-169. Doi: 10.1016/j.conbuildmat.2018.03.119

Festugato, L., Venson, G. I., & Consoli, N. C. (2021). Parameters controlling cyclic behaviour of cement-treated sand. *Transportation Geotechnics, 27*. Doi: 10.1016/j.trgeo.2020.100488

Firoozi, A. A., Guney Olgun, C., Firoozi, A. A., & Baghini, M. S. (2017). Fundamentals of soil stabilization. *International Journal of Geo-Engineering, 8*(1), 26. Doi: 10.1186/s40703-017-0064-9

Gnanendran, C. T., & Piratheepan, J. (2008). Characterisation of a lightly stabilised granular material by indirect diametrical tensile testing. *International Journal of Pavement Engineering, 9*(6), 445-456. Doi: 10.1080/10298430802342732

Hall, K. T., Correa, C. E., Carpenter, S. H., & Elliot, R. P. (2001). Rehabilitation strategies for highway pavements. *National Cooperative Highway Research Program, Web Document, 35*.

Horpibulsuk, S., Katkan, W., Sirilerdwattana, W., & Rachan, L. (2006). Strength development in cement stabilized low plasticity and coarse grained soils: Laboratory and field study. *Soils and Foundations, 46*(3).

Horpibulsuk, S., Rachan, R., Chinkulkijniwat, A., Raksachon, Y., & Suddeepong, A. (2010). Analysis of strength development in cement-stabilized silty clay from microstructural considerations. *Construction and Building Materials, 24*, 2011-2021. Doi: 10.1016/j.conbuildmat.2010.03.011

Imtiaz, T., Ahmed, A., Hossain, M. S., & Faysal, M. (2020). Microstructure Analysis and Strength Characterization of Recycled Base and Sub-Base Materials Using Scanning Electron Microscope. *Infracstructure, 5*(070). Doi: 10.3390/infrastrures 5090070

Jameson, G. (2008). *Guide to pavement technology: part 2: pavement structural design*.

Jitsangiam, P., Nusit, K., Chummuneerat, S., Chindaprasirt, P., & Pichayapan, P. (2016a). Fatigue Assessment of Cement-Treated Base for Roads: An Examination of Beam-Fatigue Tests. *Journal of Materials in Civil Engineering, 28*(10). Doi: 10.1061/(asce)mt.1943-5533.0001601

Jitsangiam, P., Nusit, K., Chummuneerat, S., Chindaprasirt, P., & Pichayapan, P. (2016b). Fatigue Assessment of Cement-Treated Base for Roads: An Examination of Beam-Fatigue Tests. *Journal of Materials in Civil Engineering, 28*(10), 04016095. Doi: 10.1061/(ASCE)MT.1943-5533.0001601

Jose, A., & Kasthurba, A. K. (2020). Laterite soil-cement blocks modified using natural rubber latex: Assessment of its properties and performance. *Construction and Building Materials*. Doi: 10.1016/j.conbuildmat.2020.121991

Kavussi, A., & Modarres, A. (2010). Laboratory fatigue models for recycled mixes with bitumen emulsion and cement. *Construction and Building Materials, 24*(10), 1920-1927. Doi: 10.1016/j.conbuildmat.2010.04.009

Khedr, S. (1985). Deformation characteristics of granular base course in flexible pavements. *Transportation Research Record, 1043*, 131-138.

Khoury, N., & Zaman, M. M. (2007). Durability of stabilized base courses subjected to wet–dry cycles. *International Journal of Pavement Engineering, 8*(4), 265-276. Doi: 10.1080/10298430701342874

Li, N., Lv, S., Wang, W., Guo, J., Jiang, P., & Liu, Y. (2020). Experimental investigations on the mechanical behavior of iron tailings powder with compound admixture of cement and nano-clay. *Construction and Building Materials, 254*. Doi: 10.1016/j.conbuildmat.2020.119259

Li, Q., & Hu, J. (2020). Mechanical and Durability Properties of Cement-Stabilized Recycled Concrete Aggregate. *Sustainability, 12*(18). doi:10.3390/su12187380

Lv, S., Xia, C., Liu, H., You, L., Qu, F., Zhong, W., . . . Washko, S. (2019). Strength and fatigue performance for cement-treated aggregate base materials. *International Journal of Pavement Engineering, 22*(6), 690-699. Doi: 10.1080/10298436.2019.1634808

Modarres, A., & Bengar, P. A. (2017). Investigating the indirect tensile stiffness, toughness and fatigue life of hot mix asphalt containing copper slag powder. *International Journal of Pavement Engineering, 20*(8), 977-985. Doi: 10.1080/10298436.2017.1373390

Moffat, M. A., Sharp, K. G., Vertessy, N. J., Johnson-Clarke, J. R., Vuong, B. T., & Yeo, R. E. Y. (1998). The performance of in situ stabilised marginal sandstone pavements. *APRG Rep. No. 22 and ARRB TR Re search Rep. No 322, Australia*.

Mohammad, L. N., Puppala, A. J., & Alavilli, P. (1994). Effect of strain measurements on resilient modulus of sands. *ASTM Special Technical Publication, 1213*, 202-202.

Muhammad, B., & Ismail, M. (2012). Performance of natural rubber latex modified concrete in acidic and sulfated environments. *Cement and Concrete Research, 31*, 129-134. Doi: 10.1016/j.conbuildmat.2011.12.099

Paul, D. K., & Gnanendran, C. T. (2016). Characterization of Lightly Stabilized Granular Base Materials Using Monotonic and Cyclic Load Flexural Testing. *Journal of Materials in Civil Engineering, 28*(1), 04015074. Doi: 10.1061/(ASCE)MT.1943-5533.0001302

Paul, D. K., Theivakularatnam, M., & Gnanendran, C. T. (2015). Damage Study of a Lightly Stabilised Granular Material Using Flexural Testing. *Indian Geotechnical Journal, 45*(4), 441-448. Doi: 10.1007/s40098-015-0158-2

Piratheepan, J., Gnanendran, T., & Lo, S.-C. R. (2010). Characterization of Cementitiously Stabilized Granular Materials for Pavement Design Using Unconfined Compression and IDT Testings with Internal Displacement Measurements. *Journal of Materials in Civil Engineering, 22*(5), 495-505. Doi: 10.1061/(ASCE)MT. 1943-5533.0000051

Pretorius, P. C., & Monismith, C. L. (1972). Fatigue Crack Formation and propagation in pavements containing soi-cement bases. *Highway Research Record, 407*, 102–115.

Rao Tangella, S. C. S., Craus, J., Deacon, J. A., & Monismith, C. L. (1990). Summary report on fatigue response of asphalt mixtures. *Institute for Transportation Studies, Univ. of California, Berkeley, CA*.

Sariosseiri, F., & Muhunthan, B. (2009). Effect of cement treatment on geotechnical properties of some Washington State soils. *Engineering Geology, 104*(1-2), 119-125. Doi: 10.1016/j.enggeo.2008.09.003

Sobhan, K., & Das, B. M. (2007). Durabillity of soil cements against fatigue frature. *Journal of Materials in Civil Engineering, 19*(1), 26-32. Doi:10.1061/(ASCE)0899-1561(2007)19:1(26)

Sounthararajah, A., Bui, H. H., Nguyen, N., Jitsangiam, P., & Kodikara, J. (2018). Early-Age Fatigue Damage Assessment of Cement-Treated Bases under Repetitive Heavy Traffic Loading. *Journal of Materials in Civil Engineering, 30*(6). Doi: 10.1061/(asce)mt.1943-5533.0002250

Sudla, P., Horpibulsuk, S., Chinkulkijniwat, A., Arulrajah, A., Liu, M. D., & Hoy, M. (2018). Marginal lateritic soil/crushed slag blends as an engineering fill material. *Soils and Foundations, 58*. Doi: 10.1016/j.sandf.2018.03.007

Thompson, M. R., & Smith, K. L. (1990). Repeated triaxial characterization of granular bases. *Transportation Research Record, 1278*, 7-17.

Tingle, J. S., & Santoni, R. L. (2003). Stabilization of Clay Soils with Nontraditional Additives. *Transportation research board, 1819*(1). Doi: 10.3141/1819b-10

Tran, N. Q., Hoy, M., Suddeepong, A., Horpibulsuk, S., Kantathum, K., & Arulrajah, A. (2022). Improved mechanical and microstructure of cement-stabilized lateritic soil using recycled materials replacement and natural rubber latex for pavement applications. *Construction and Building Materials, 347*. Doi: 10.1016/j.conbuildmat.2022.128547

Udomchai, A., Buritatum, A., Suddeepong, A., Hoy, M., Horpibulsuk, S., Arulrajah, A., & Horpibulsuk, J. (2021). Evaluation of durability against wetting and drying cycles of cement-natural rubber latex stabilised unpaved road under cyclic tensile loading. *International Journal of Pavement Engineering*, 1-12. Doi: 10.1080/10298436.2021.1950719

Vo, M. L., & Plank, J. (2018). Evaluation of natural rubber latex as film forming additive in cementitious mortar. *Construction and Building Materials, 169*, 93-99. Doi: 10.1016/j.conbuildmat.2017.12.098

Vollmert, L. (2021). Reduction of accumulated plastic deformations in base courses. In *Green and Intelligent Technologies for Sustainable and Smart Asphalt Pavements* (pp. 579-582): CRC Press.

Werkmeister, S. (2003). Permanent deformation behaviour of unbound granular materials in pavement constructions. *Ph.D. dissertation, TU Dresden, Dresden*.

Wilmot, T., & Rodway, B. (1999). Stabilized pavements- Selecting the additive: cementitious, polimer or bitumen *he International Congress on Local Government Engineering & Public Works*.

Yaowarat, T., Horpibulsuk, S., Arulrajah, A., Maghool, F., Mirzababaei, M., Rashid, A. S. A., & Chinkulkijniwat, A. (2020). Cement stabilization of recycled concrete aggregate modified with polyvinyl alcohol. *International Journal of Pavement Engineering*. Doi: 10.1080/10298436.2020.1746311

Yaowarat, T., Sudsaynate, W., Horpibulsuk, S., Chinkulkijniwat, A., Arulrajah, A., & Horpibulsuk, J. (2021). Mechanical properties of fly ash–asphalt emulsion geopolymer stabilized crushed rock for Sustainable pavement base. *Journal of Materials in Civil Engineering, 33*(9), 04021220.

CHAPTER V

WETTING-DRYING DURABILITY PERFORMANCE OF CEMENT-STABILIZED RECYCLED MATERIALS AND LATERITIC SOIL USING NATURAL RUBBER LATEX FOR SUSTAINABLE PAVEMENT MATERIALS

5.1 Introduction

In recent decades, greenhouse gas emissions, particularly CO_2 proved to be the main cause of climate change (DCLG, 2006), which is an interesting subject that has attracted the attention of many researchers. In construction, several arguments suggest that the built environment is one of the largest contributors to global climate change concerning CO_2 emissions, water consumption, landfill waste, and used raw materials (BERR, 2008). In addition, construction and industrial waste are becoming an environmental burden in many industrial cities of developed and developing countries around the world. With awareness and the environmental problem of waste materials, many governments and researchers have attempted to innovate and increase eco-friendly solutions in solving these such materials. The usage of recyclable construction and industrial wastes in civil infrastructure to replace natural materials enables minimizing the use of quarried materials, reducing energy consumption, and decreasing waste and greenhouse gas emissions to the environment, driving toward sustainable development in construction.

Many researchers have evaluated the potential of waste materials in partial or total replacement to natural material resources in construction. Especially, construction and demolition (C&D) materials and by-products such as reclaimed asphalt pavement (RAP), recycled concrete aggregate (RCA), crushed brick (CB), plastic polyethylene terephthalate, steel slag (SS) have been assessed to be useful to replace natural materials in pavement application (Busari, Adeyanju, Loto, & Ademola, 2019;

Huang, Bird, & Heidrich, 2007; Pereira & Vieira, 2022; Salehi, Arashpour, Kodikara, & Guppy, 2021).

The materials improvement technique has also been studied worldwide to more effectively apply recyclable materials to satisfy the increasing demand for pavement quality. In which, stabilization material is being studied extensively to solve the issue of scarcity of good quality aggregates and enhance the performance of the pavement. In some countries in Southeast Asia, cement stabilized materials is one of the most preferred options because of its economy and performance improvement effectiveness (Biswal, Sahoo, & Dash, 2018; Buritatun et al., 2022a; Buritatun et al., 2020; Horpibulsuk, Katkan, Sirilerdwattana, & Rachan, 2006; Horpibulsuk, Rachan, Chinkulkijniwat, Raksachon, & Suddeepong, 2010; Sudla et al., 2019). With the cement addition, the calcium silicate hydrate (C-S-H), calcium aluminum hydrate (C-A-H), and calcium hydroxide ($Ca(OH)_2$) are produced by the hydration reaction, which contribute to the bond between soil particles and fill voids in the matrix and consequently strengthen cement stabilized structure satisfying the requirements in the construction field (Walker & Stace, 1997; Xing, Yang, Xu, & Ye, 2009; Xiong, Xing, & Li, 2019). Besides the undeniable effectiveness of cement stabilized materials, it exhibits unfavorable characteristics such as shrinkage and cracking in pavement base structure due to the rapid moisture loss. The polymer additives application has been proven effective not only in enhancing the strengths but also improving the brittle behavior of pavement structure against the tensile and flexural stresses, which are caused by the wheel loads and the weather temperature (Baghini, Ismail, Naseralavi, & Firoozi, 2016; Estabragh, Beytolahpour, & Javadi, 2011; Jose & Kasthurba, 2020; Tingle & Santoni, 2003; Yaowarat et al., 2020; Yaowarat, Sudsaynate, et al., 2021; Zalnezhad & Hesami, 2020).

Natural rubber latex (NRL) is a biopolymer of the Hevea brasiliensis tree. It is produced with a large amount by Southeast Asia countries in which Thailand, Vietnam, and Indonesia are the top three producers providing around 50% of total rubber production worldwide. Hence, NRL research and application as a sustainable additive in construction have been encouraged by governments. The NRL applications in the pavement have been reported in many previous studies. Wen, Wang, Zhao, and Sumalee (2017) reported that the elasticity of NRL can improve the viscosity and elastic recovery of asphalt binders. Muhammad and Ismail (2012) proved that an appropriate addition of NRL could reduce the interparticle gaps and transform the concrete microstructure into a relatively denser matrix, restricting the fluid flow into and within the modified phases and therefore curbing attack from H_2SO_4 and Na_2SO_4. Especially, the application of NRL in improving the reliability and performance of cement-stabilized recycled materials and soils blends has also been proven in several studies (Buritatun et al., 2020; Dv, Hoy, Karntatam, Arulrajah, & Horpibulsuk, 2022; Tran et al., 2022) by forming the rubber films and filling the pore space within the stabilized matrix, leading to a stronger stabilized structure. However, the performances of materials are improved by the appropriate amount of NRL (optimum NRL content). Beyond this optimum, the strength of materials tends to decrease because the excess NRL creates a thicker film covering the aggregate-cement matrix and retarded the hydration process. The optimum NRL contents have been found to be different for diverse material blends and cement contents. Indeed, Buritatun et al. (2020) report that the highest unconfined compressive and flexural strengths of cement-NRL stabilized soil were obtained when 20%, 15%, and 10% NRL additive replacement of cement by weight for the samples with 3%, 5%, and 7% cement contents, respectively. For the cement stabilized recycled concrete aggregate, Dv et al. (2022) indicated that the optimum r/c ratios of 10%, 5%, and 5% provided the maximum unconfined compressive strength and tensile strength values of cement-NRL stabilized recycled concrete aggregate at 3%, 5%, and 7% cement contents, respectively. Cement-NRL stabilized recycled materials and lateritic soil blends got the highest strength at 3% and 5% of r/c ratios for steel slag-lateritic soil and recycled concrete aggregate-lateritic soil blends, respectively (Tran et al., 2022). Therefore, the NRL application in pavement construction should be researched for different materials.

Though the strength in terms of unconfined compressive strength (UCS) is one of the fundamental parameters used to assess the suitability of stabilized materials to be the pavement base or subbase layer, the performance of stabilized base materials and thereby the pavement depends on the durability against the cyclic change of weather or environmental features. The durability of pavement can be defined as the ability of the material to retain stability and integrity over a number of years of exposure to the action of weathering (Shihata & Baghdadi, 2001). The environmental features including freeze-thaw and wet-dry cycles are considered to be the most destructive actions, which damage the pavement structure (Khoury & Zaman, 2007; Portland Cement Association, 1992). The wet-dry cycle is considered to have a much more detrimental impact on the strength of pavement base structure than the freeze-thaw cycle in tropical countries where the cycle of wet and dry seasons is one of the main reasons leading to cracking problems and premature stabilized pavement distress. Hence, durability against wetting-drying cycles of stabilization materials has been widely studied in recent years (Cuisinier & Masrouri, 2020; Donrak et al., 2018; Hoy, Rachan, Horpibulsuk, Arulrajah, & Mirzababaei, 2017; James, Sivapriya, Ali, Madhu, & Singh, 2021; Li & Hu, 2020; Soldo & Miletic, 2022). Most of studies results showed that the mechanical properties of stabilized materials decrease with the increase of the number of wetting-drying cycles.

Therefore, the natural rubber latex was investigated to evaluate its effectiveness in the improvement of wetting-drying resistance of cement-stabilized lateritic soil with RCA and SS as pavement base materials. The weight loss, water absorption, unconfined compressive strength, and scanning electron microscopy (SEM) were performed. The recycled materials replacements, dry rubber-to-cement ratios, and wetting-drying cycles were the influence factors in this research. This research outcome will demonstrate the effective utilization of NRL as a natural polymer for pavement application.

5.2 Materials and methods

5.2.1 Materials

To investigate the effect of natural rubber latex on the durability against wetting-drying cycle of cement stabilized recycled materials and lateritic soil blends, two of recycled materials including steel slag (SS) and recycled concrete aggregate (RCA) were used in this study. SS is the by-product collected from the Siam Steel Mill Services Co., Ltd., Chonburi province, Thailand, and RCA is the demolition concrete waste obtained from Nakhon Ratchasima province. Lateritic soil (LS) was excavated from the borrow pit in Nakhon Ratchasima province, Thailand. A series of laboratory tests were undertaken to determine the grain size distribution (ASTM-D422-63) and engineering properties of studied aggregates, which include plasticity index (ASTM-D4318-05), specific gravity and water absorption (ASTM-C127-15), modified compaction (ASTM-D1557-09), California bearing ratio (ASTM-D1883-07), Los Angeles abrasion (ASTM-C131/C131M-14), and flakiness index (ASTM-D4791-99).

The grain size distribution of air-dried aggregates was determined by the sieve analysis method in accordance with ASTM-D422-63 (2007) and their curves are shown in Figure 5.1. Based on the Unified Soil Classification System (USCS) (ASTM-D2487-06), SS and RCA were classified as GW (Well-graded gravel with sand) while LS was classified as GC (Clayey gravel with sand). SS or RCA would be replaced for LS at designed ratios of 50% and 70% to create blends (**Figure 5.1**) that meet the requirement for cement stabilized pavement base materials specified by the Department of Highway (DOH), Thailand, similar to AASHTO M147.

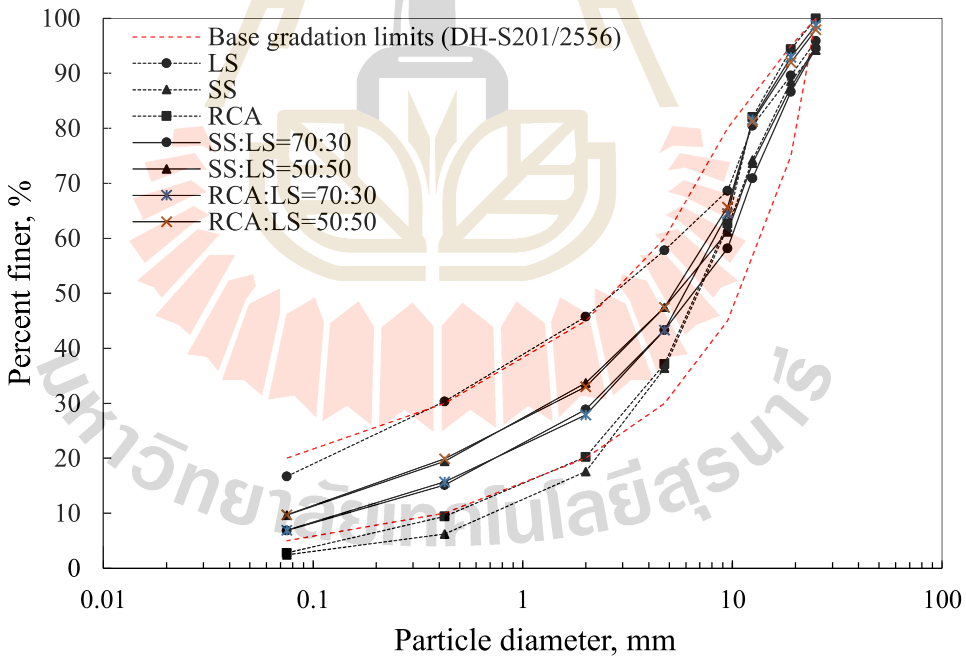


Figure 5.1 Grain size distribution of studied mixes.

The specific gravity of SS, RCA, and LS was found to be 3.64, 2.57, and 2.78, respectively. SS and RCA were found non-plastic materials while 21% and 8%

were the liquid limit and plastic limit of LS, respectively. The compaction behaviors of SS, RCA, and LS were expressed by the maximum dry density of 2700 kg/m^3, 1960 kg/m^3, and 2130 kg/m^3, respectively, at the optimum water content of 6.04, 12.0, and 8.07%. The Los Angeles (LA) abrasion resistance of studied materials is expressed by the LA abrasion values that were found to be 17.2, 31.0, and 34.0% for SS, RCA, and LS, respectively. These values show that the LA abrasion resistance of SS and RCA is higher than that of LS, in which, SS has the greatest LA abrasion resistance with a significantly lower LA abrasion value (17.2). While LA abrasion values of studied materials meet the maximum allowable value of 40%, California bearing ratio (CBR) values of SS, RCA, and LS were 58, 43, and 18%, respectively, unsatisfying the minimum requirement of 80% for base materials designed by DOH, Thailand. Therefore, the cement stabilization method was used to improve these materials as cement stabilized base materials following the guideline of DOH, Thailand.

Cement and natural rubber latex (NRL) were used as a compound additive in this study. Portland cement type I is characterized by the 7-day and 28-day compressive strengths of 24.7 and 32.6 MPa, respectively, while NRL liquid consisted of a total solid content of 33.06, dry rubber content of 30.8, sludge content of 2.46, and coagulum content of 0.024 percent by weight, which is classified as the low category rubber latex. The specific gravity of NRL was 0.96. NRL liquid has alkalinity with pH = 8, which is advantageous to the cement hydration process.

5.2.2 Sample preparation

SS, RCA, and LS aggregates were air-dried and removed the 19mm-coarser particles before being used in this research. SS or RCA was blended with LS at two different ratios of 70:30 and 50:50 to create four blends, namely SS:LS=70:30, SS:LS=50:50, RCA:LS=70:30, and RCA:LS=50:50. 5% cement content by weight was used as the chemical additive for stabilization blends. Tran et al. (2022) conducted research on cement-NRL stabilized SS:LS and RCA:LS at various r/c ratios and the results showed that the highest UCS values were found at an optimum r/c ratio of 3% for SS:LS blends and 5% for RCA:LS blends. Hence, the range of r/c ratio from 0% to 5% was selected to evaluate the durability of studied blends against wetting-drying cycles. The samples with 3% and 5% of r/c ratios were compared to samples with 0% of r/c ratio (without

NRL) to evaluate the effect of NRL on the durability of cement stabilized SS:LS and RCA:LS blends.

In order to prepare samples for this research, the modified compaction (ASTM-D1557-12) was preconducted to obtain the optimum water content (OWC) and maximum dry density (MDD) of each studied blend, which were used to prepare mixtures for molding. The mixing procedure includes 2 stages. The first stage was mixing the air-dried LS and recycled materials (SS/RCA) with cement powder to create the homogeneous SS:LS=70:30, SS:LS=50:50, RCA:LS=70:30, and RCA:LS=50:50 blends. The second stage continued to mix these blends with water or water-NRL to produce the cement stabilized mixes or cement-NRL stabilized mixes, respectively. Mixtures were compacted in five layers in the steel mold under modified compaction effort (2700 kN-m/m^3) to create cylindrical samples with a diameter of 101.6 mm and a height of 116.8 mm. Subsequently, samples were demolded after 24 hours and wrapped by plastic sheets. These compacted samples were cured in the humidity of 95% and temperature 25^{o}C controlled room for 28 days before testing.

5.2.3 Experimental procedures

The durability against wetting-drying (w-d) cycles was conducted on 28-day cured samples in accordance with ASTM (ASTM-D559-03). Three stages include immersing samples in temperature-controlled potable water for 5 hours, then drying samples in the oven at 70^{o}C for 42 hours, and finally air-drying for 1 hour, which constitute a 48-hour w-d cycle (Figure 5.2). In this study, the samples were subjected to 15 w-d cycles. The sample weight was noted after immersing and drying stages of each cycle to evaluate durability in terms of percent weight loss and water absorption of samples due to the repeated w-d cycles. At the target w-d cycles of 1, 3, 6, 9, 12, and 15, the samples were immersed in deionized water for 2 hours and then air-dried for 1 hour for the UCS test. Each value reported in this paper is the average of three samples that were prepared and tested in the same condition to ensure the reliability of the results (ASTM-D1633-17).

Unconfined compressive strength (UCS) is the common practice to determine the strength of cement stabilized soil samples from the unconfined compression test. UCS is considered to be the one of the most important parameters in road construction and earth work applications (Yarbaşı, Kalkan, & Akbulut, 2007). In this study, unconfined compressive strength test was also conducted on 7-day and 28-day samples to ensure the designed blends and additives are suitable as pavement base materials, which meet the minimum strength requirement specified by DOH.

Scanning electron microscopy (SEM) was performed to clarify the changes in sample microstructure due to the repeated w-d cycles. SEM samples were collected from broken fragments after UCS test. The liquid nitrogen was applied to immobilize the samples for about five minutes prior to evacuation at a pressure of 0.5 Pascal at –40 °C for five days. The samples were then coated with gold prior to SEM analysis.

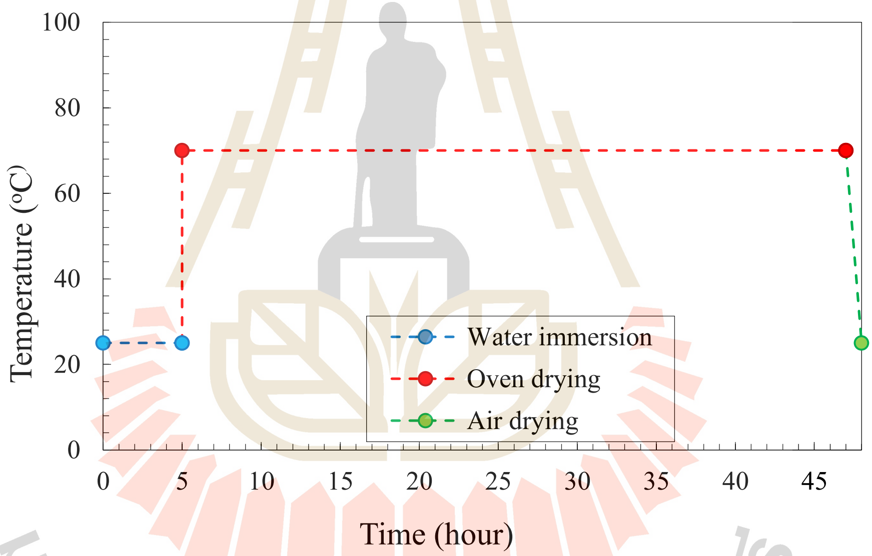


Figure 5.2 The procedure of one wetting-drying cycle.

5.3 Results and discussion

5.3.1 Unconfined compressive strength (UCS)

The strength in term of unconfined compressive strength (UCS) is one of the most crucial parameters used to assess the suitability of stabilized materials to be the pavement base or subbase layer. The minimum unconfined compressive strength of the 7-day cement-stabilized sample specified in Thailand Department of Highways (DOH) (DH-S204/2556) is 1.724 MPa for low traffic volume roads and 2.413 MPa for high traffic volume roads. In addition, ACI 230 (2009) and Little DN and S. (2009)

recommended the requirement for 28-day UCS of cement stabilized sandy and gravel soils to be between 2.67 MPa and 6.89 MPa.

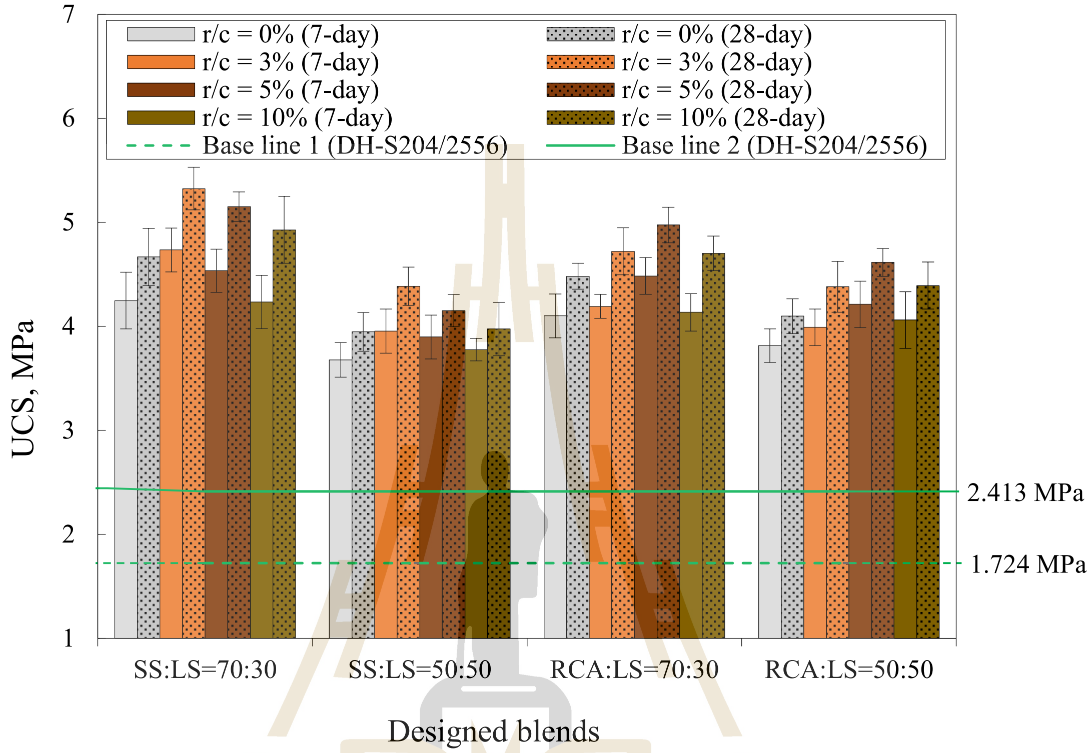


Figure 5.3 7-day and 28-day unconfined compressive strength of cement-NRL stabilized SS:LS=70:30, SS:LS=50:50, RCA:LS=70:30, and RCA:LS=50:50 samples at 0%, 3%, 5%, and 10% of r/c ratios.

Figure 5.3 illustrates the 7-day and 28-day UCS results of cement-NRL stabilized SS:LS=70:30, SS:LS=50:50, RCA:LS=70:30, and RCA:LS=50:50 samples at the various r/c ratios of 0%, 3%, 5%, and 10%. The results show that the 7-day UCS of all cement stabilized and cement-NRL stabilized samples meet the minimum strength requirement specified by Thailand Department of Highway for cement-stabilized pavement base materials for both low and high volume traffic roads. In addition, the 28-day UCS values of all samples are from 3.77 MPa to 5.32 MPa which satisfied the range between 2.67 MPa and 6.89 MPa recommended by ACI 230 (2009) and Little DN and S. (2009). It proved that the designed blends and additive content are suitable for the stabilization pavement base course. The UCS results also clearly indicate that the stabilized samples with NRL (at r/c ratios of 3%, 5%, and 10%) produced higher UCS than stabilized samples without NRL (at r/c ratio of 0%). This is due to the rubber films formed by NRL addition could fill up the pore spaces and increase the interparticle bonding strength within the stabilization network, resulting in UCS improvement (Tran et al., 2022). The highest UCS values were found at r/c ratios of 3% and 5% for cement-NRL stabilized SS:LS samples and RCA:LS samples, respectively, which proved that 3% and 5% are the optimum r/c ratios of cement-NRL stabilized SS:LS and RCA:LS, respectively. The UCS values of cement-NRL stabilized SS:LS and RCA:LS blends at both 70:30 and 50:50 ratios increase with curing time, which is completely similar to previous studies on cement stabilized materials (Barišić, Dimter, & Rukavina, 2015; Horpibulsuk et al., 2006; Horpibulsuk et al., 2010; Li & Hu, 2020) and cement-NRL stabilized materials (Buritatun et al., 2020; Dv et al., 2022).

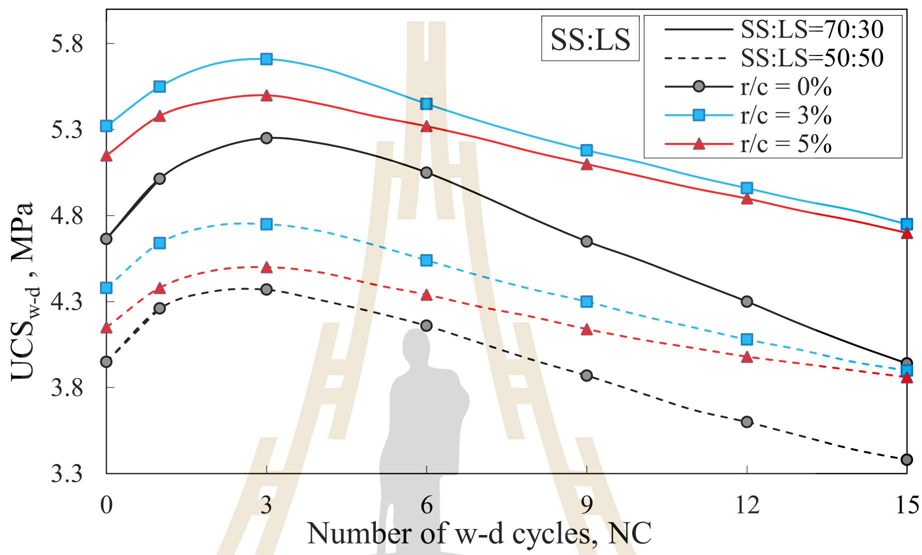
5.3.2 Durability against wetting-drying cycles

The UCS, weight loss, water absorption, and microstructural change of samples were considered as the results of the wetting-drying test that was conducted on the 28-day cement-NRL stabilized SS:LS and RCA:LS samples at various r/c ratios (0%, 3%, and 5%) to investigate the effect of NRL on the durability of studied samples against wetting-drying cycles.

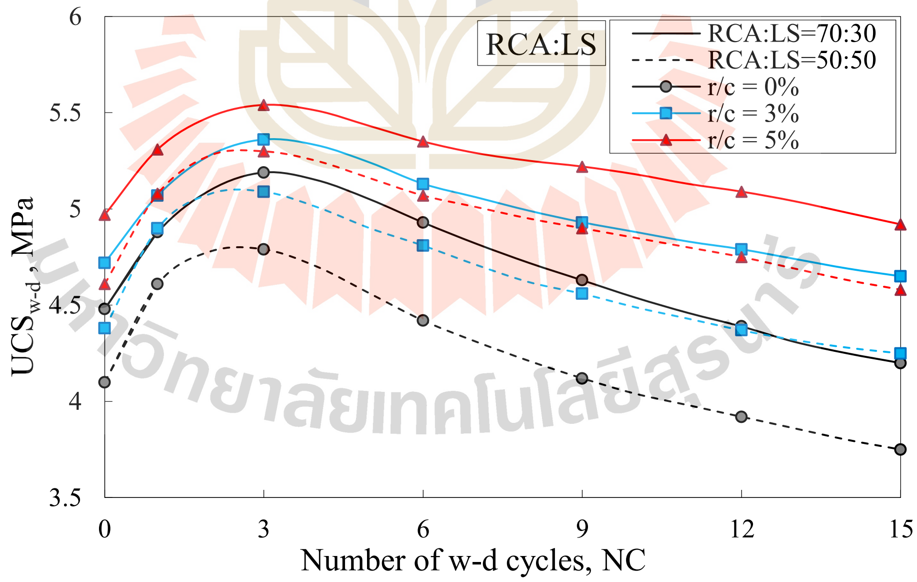
Figure 5.4 presents the relationship between unconfined compressive strength after wetting-drying cycles (UCS_{w-d}) versus the number of w-d cycles (NC) of cement-NRL stabilized SS:LS=70:30, SS:LS=50:50, RCA:LS=70:30, and RCA:LS=50:50 at different r/c ratios of 0%, 3%, and 5%. The results show that the UCS_{w-d} development with an increase of NC was observed for all samples, up to 3 cycles and then decreased beyond 3 cycles. The UCS_{w-d} remarkably increased after the first cycle and then slightly increased up to the third cycle prior to the decrease. This variation was found the same for all samples with and without NRL at both 70:30 and 50:50 ratios of SS/RCA:LS blends. In several previous studies, the UCS_{w-d} development of stabilized samples in initial w-d cycles was found to occur simultaneously with the growth of cementitious products during the w-d process (Hoy et al., 2017; Sivapullaiah & Moghal, 2011). The main chemical compositions of LS include a high content of silica (75.51%) and alumina (14.28%) while SS consists of 25.47% silica and 22.24% calcium. Silica and calcium with contents of 36.4% and 52.48%, respectively, were also found in RCA material (Tran et al., 2022). The formation of Calcium Silicate Hydrate (C-S-H) and Calcium Aluminate Hydrate (C-A-H) from the chemical reaction between silica and alumina with calcium in studied materials combined with the hydration products from Portland cement, which assisted in maintaining and enhancing the strength of cement stabilized and cement-NRL samples after several initial cycles (Du, Bo, Jin, & Liu, 2016). Furthermore, the composition of Portland cement includes gypsum, which essentially contributes to the growth of cementitious compounds during the wetting-drying process and this is sustainable with repeated w-d cycles (Sivapullaiah & Moghal, 2011). In the 70°C dried process, the temperature increase promotes the moisture diffusivity of cementitious materials and thus chemical reaction (Drouet, Poyet, & Torrenti, 2015; Jooss & Reinhardt, 2002), leading to the increment of cement hydration products (C-S-H) (Brue, Davy, Skoczylas, Burlion, & Bourbon, 2012). With NC >3, the UCS decrease with the increase of w-d cycles was noted for all cement stabilized and cement-NRL SS:LS and RCA:LS samples. This reduction is attributed to the Ca^{2+} leaching from the cement stabilized materials subjected to the soaking condition and the dissolution of $Ca(OH)_2$/C-S-H formed in the stabilized matrix, which is indicated in previous studies (Du, Jiang, Shen, & Jin, 2012; Shen, Han, & Du, 2008). Moreover, the sample structure no longer retained its monolithicity due to the loss of moisture and the particle bondings gradually become looser and lose their cohesion. The crack propagation and extension gradually caused the crumbling, fragmenting, and splintering of samples, resulting in the deterioration and strength loss of samples.

At different recycled materials (SS or RCA), it is clearly shown that the 28-day UCS and UCS_{w-d} produced by cement-NRL stabilized SS:LS blends were higher than those of cement-NRL stabilized RCA:LS blends at both 70:30 and 50:50 of SS/RCA:LS ratios. This was explained by the previous studies that the engineering properties of blends are contributed by Los Angeles abrasion resistance of materials. The Los Angeles abrasion of SS (17.2%) was found to be lower than that of RCA (31%) and LS (34%), which lead to the better mechanical properties of SS:LS blends compared to RCA:LS blends (Sudla et al., 2019; Tran et al., 2022). For the particular type of recycled material, cement-NRL stabilized SS:LS=70:30 and RCA:LS=70:30

expressed the higher $UCS_{w\text{-}d}$ than cement-NRL stabilized SS:LS=50:50 and RCA:LS=50:50 blends, respectively. The lower Los Angeles abrasion of SS and RCA compared to LS could contribute to the stronger structure and thereby the higher strength for samples with higher SS/RCA content.



(a)



(b)

Figure 5.4 UCS of cement-NRL stabilized (a) SS:LS blends and (b) RCA:LS blends at various r/c ratios and different target w-d cycles of 1, 3, 6, 9, 12, and 15.

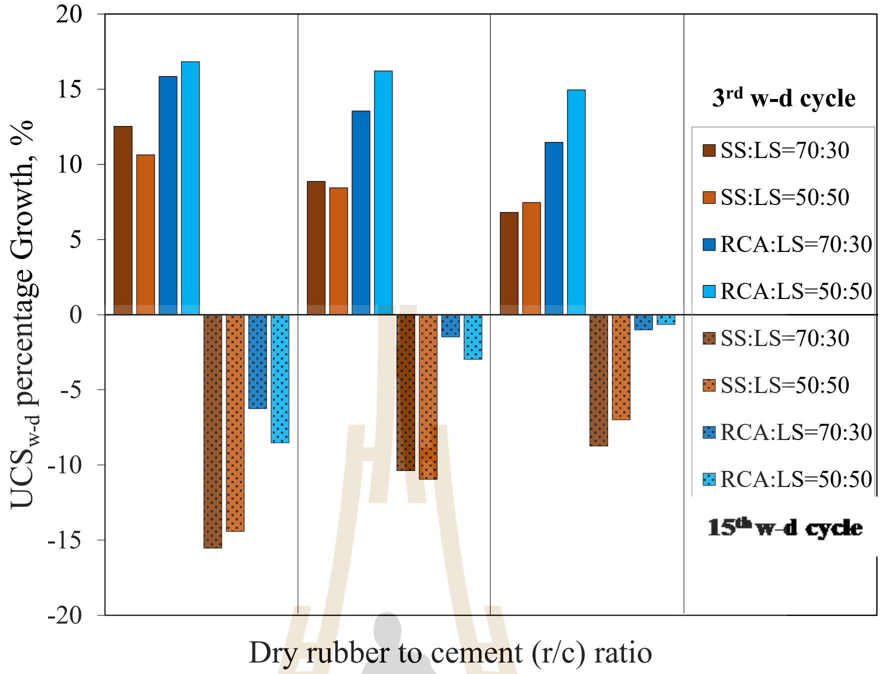
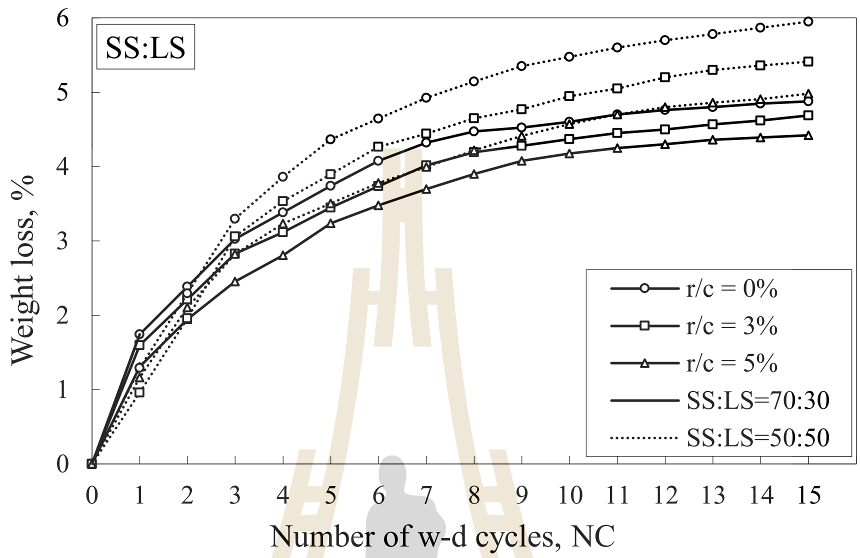
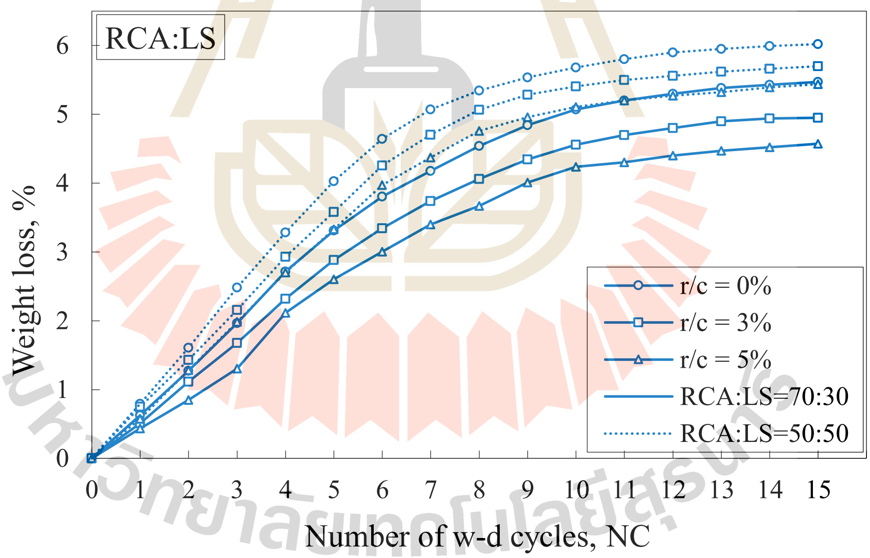


Figure 5.5 UCS$_{w-d}$ percentage growth of cement-NRL stabilized SS:LS and RCA:LS samples at the 3rd and 15th w-d cycles

The UCS$_{w-d}$ percentage growth of samples at the third and fifteenth cycles was presented in Figure 5.5. In which, the positive and negative values represent the increase and decrease of UCS$_{w-d}$, respectively, compared to UCS$_{28-day}$. The UCS$_{w-d}$ of cement-NRL stabilized SS:LS and RCA:LS samples at the third cycle increased 6.7% - 12.5% and 11.4% - 16.8%, respectively. Whereas, UCS$_{w-d}$ at the end of the w-d test was found to be reduced by 7.0% - 15.5% and 0.5% - 8.5% for cement-NRL stabilized SS:LS and RCA:LS, respectively. A noteworthy observation is that the UCS$_{w-d}$ of cement-NRL stabilized RCA:LS samples exhibited a higher growth percentage at the third cycle and a lower reduction percentage at the fifteenth cycle compared to cement-NRL stabilized SS:LS samples. This might be attributed by the higher degree of chemical reaction due to the higher amount of CaO and SiO_2 in RCA than in SS (Tran et al., 2022). The results also show that the growth percentage of UCS$_{w-d}$ at the third cycle was lower at the higher r/c ratios. This is because the NRL film retarded the cement hydration process, reducing the hydration products of cement stabilized samples (Buritatun et al., 2020; Tran et al., 2022). However, the UCS$_{w-d}$ reduction percentage at the end of the w-d test was lower for samples with higher r/c ratios. This proved that the NRL films could improve the w-d subjected resistance of cement stabilized samples and maintain their strength under wetting-drying conditions.



(a)

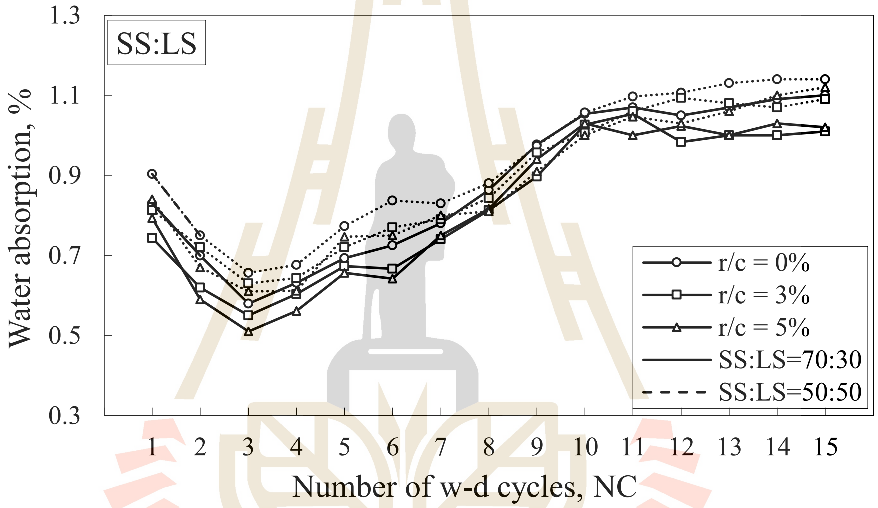


(b)

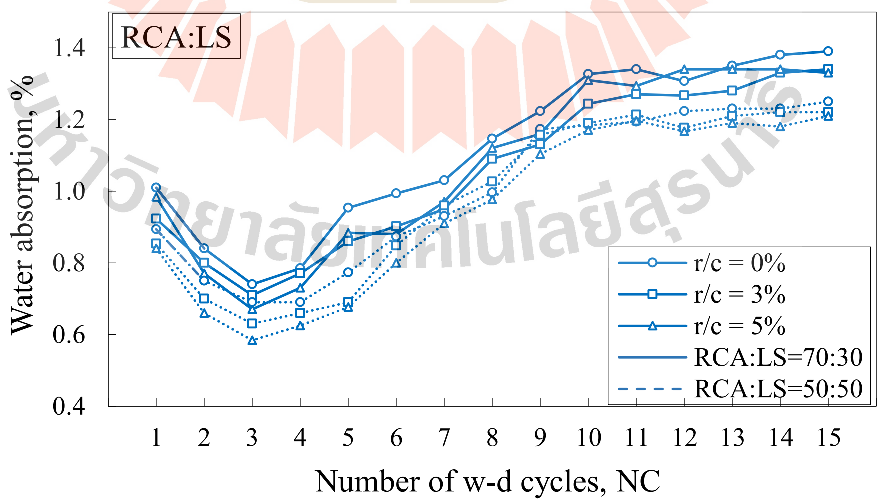
Figure 5.6 The weight loss of cement-NRL stabilized (a) SS:LS blends and (b) RCA:LS blends at different numbers of w-d cycles.

Figure 5.6 illustrates the relationship between weight loss of cement stabilized SS/RCA:LS and cement-NRL stabilized SS/RCA:LS samples versus the number of w-d cycles (NC). A significant weight loss was observed for cement-NRL stabilized

SS:LS and RCA:LS at both 70:30 and 50:50 ratios in several first cycles until NC = 4 and thereafter it slightly increased with the increase of NC. During the w-d process, it was found that the weight loss of cement-NRL SS:LS=50:50 and RCA:LS=50:50 samples were greater than those of cement-NRL stabilized SS:LS=70:30 and RCA:LS=70:30 samples, while cement-NRL stabilized SS:LS and cement-NRL stabilized RCA:LS samples exhibited the similar weight loss at the same recycled materials replacement ratios (70% or 50%). Notably, SS:LS and RCA:LS samples stabilized by cement-NRL showed lower weight loss than SS:LS and RCA:LS samples stabilized by only cement.



(a)



(b)

Figure 5.7 The water absorption of cement-NRL stabilized (a) SS:LS blends and (b) RCA:LS blends at different numbers of w-d cycles.

Figure 5.7 shows the water absorption of cement-NRL SS:LS and RCA:LS samples during the w-d test. Cement-NRL stabilized SS:LS=70:30 blend expressed a lower percentage of water absorption than cement-NRL stabilized SS:LS=50:50 blend. The water absorption of SS was found to be smaller than that of LS, thus the increase in SS content would reduce the water absorption of the blend. In contrast, cement-NRL stabilized RCA:LS=70:30 blend expressed a higher percentage of water absorption than cement-NRL stabilized RCA:LS=50:50 blend, which is due to RCA possessing higher water absorption than LS, leading to the higher potential in water absorption for the RCA:LS blend containing higher RCA content.

1 cycle 3 cycles 15 cycles

(a) SS:LS=70:30, r/c ratio = 0%

1 cycle 3 cycles 15 cycles

(b) SS:LS=70:30, r/c ratio = 3%

Figure 5.8 Photos of cement-NRL SS:LS=70:30 samples at (a) r/c ratio of 0% and (b) r/c ratio of 3% at 1st, 3rd, and 15th w-d cycles.

1 cycle 3 cycles 15 cycles

(a) RCA:LS=70:30, r/c ratio = 0%

1 cycle 3 cycles 15 cycles

(b) RCA:LS=70:30, r/c ratio = 5%

Figure 5.9 Photos of cement-NRL RCA:LS=70:30 samples at (a) r/c ratio of 0% and (b) r/c ratio of 5% at 1st, 3rd, and 15th w-d cycles.

An important feature is observed in that the water absorption of cement-NRL stabilized SS/RCA:LS samples significantly decreased at the third cycle. This might be caused by the increase of the hydration products within the sample structure, leading to a denser matrix and less pore space. The water therefore hardly comes into the samples. However, the water absorption gradually increased due to the deterioration of samples after the third cycle. The results display a decline of water absorption when NRL additive was added for both SS:LS and RCA:LS blends at both 70:30 and 50:50 ratios. The results also show that the cement-NRL stabilized samples with an r/c ratio of 5% had lower water absorption than cement-NRL stabilized samples with an r/c ratio of 3%. This means that the water absorption decreases with the increase of NRL content (r/c ratio). This decrease might be due to the hydrophobic property of NRL (Jose & Kasthurba, 2020). In addition, the rubber films fill the pores and lock the capillary paths that water can flow inside cement-NRL stabilized structure. As a result, the water absorption was reduced.

Figures 5.8 and 5.9 show the physical surface of cement-NRL stabilized SS:LS and RCA:LS samples, respectively, after 1, 3, and 15 w-d cycles. The photos show that the samples were preserved almost intact after 3 first w-d cycles. This is because the bonding structure within stabilized samples was still maintained or even become stronger due to the development of hydration products in the 3 first w-d cycles, proved by the increase of UCS_{w-d}. However, at the end of the w-d test (15 cycles the cracks and surface deterioration were observed. Under further the effect of w-d cycles, the cracks gradually grow on the samples with increasing w-d cycles, leading to the UCS_{w-d} loss of cement-NRL stabilized samples. Notely, the cement-NRL stabilized RCA:LS samples were observed to be better preserved than cement-NRL stabilized SS:LS samples. Therefore, cement-NRL stabilized RCA:LS samples expressed a higher percentage of UCS_{w-d} growth and a lower percentage of UCS_{w-d} loss than cement-NRL stabilized SS:LS samples. Furthermore, cement-NRL stabilized samples show fewer cracks and surface deterioration than cement stabilized samples. This indicated that the NRL addition could enhance the structure of cement stabilized SS/RCA:LS samples by filling the pore spaces and cracks within the stabilized matrix to improve both strength and resistance of samples subjected to w-d condition.

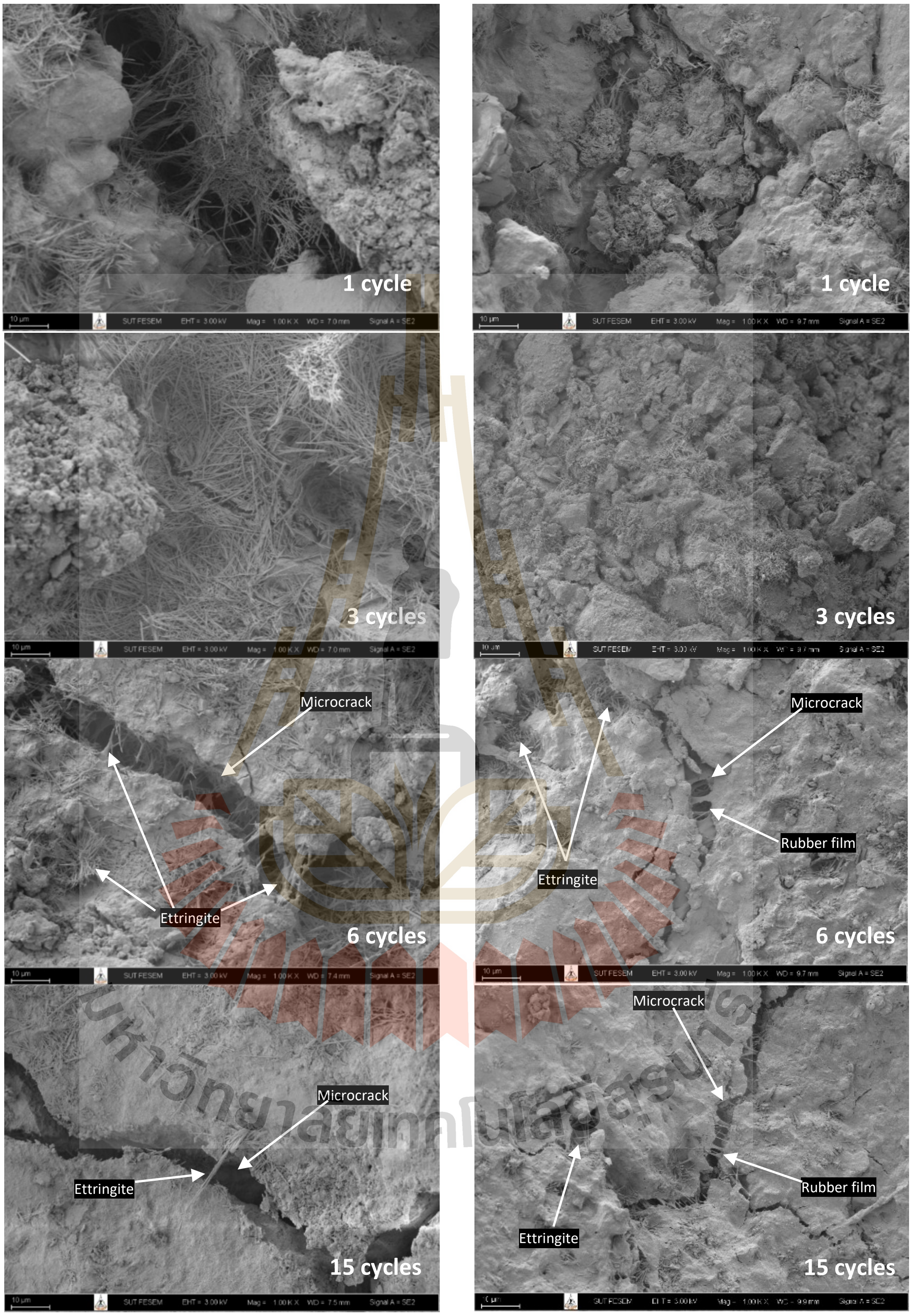
Samples with NRL produced higher UCS and UCS_{w-d} and expressed lower weight loss and water absorption than samples without NRL during the wet-dry cycles process. This is because the formation of NRL films fills up the pore spaces and microcracks to reduce the porosity and therefore decrease the permeability of cement-NRL stabilized structure, which was reported in previous studies on improving properties of cement stabilized materials, concrete, and mortar (Buritatun et al., 2020; Dv et al., 2022; Tran et al., 2022; Vo & Plank, 2018; Yaowarat, Suddeepong, et al., 2021). In other words, the presence of rubber films could reduce the water absorption of cement-NRL stabilized samples and possibly lessens the water amount coming inside the cement-NRL stabilized pavement base structure. In addition, NRL films increase the interparticle bond strength and contribute to a stronger structure, resulting in a lower percentage of weight loss over the w-d cycles. Consequently, the UCS_{w-d} of cement-NRL stabilized samples at the end of the w-d test (15 cycles) was insignificantly lower than that of samples unaffected by the w-d cycles.

5.3.3 Microstructure changes

The scanning electron microscope (SEM) was carried out to understand the change in the microstructure of cement stabilized and cement-NRL stabilized samples. Figures 5.10 and 5.11 show the SEM images of cement-NRL stabilized SS:LS=70:30 and cement-NRL stabilized RCA:LS=70:30, respectively.

Figure 5.10 illustrates the development of cementitious products and structure change of cement-NRL stabilized SS:LS=70:30 samples at r/c ratios of 0% and 3% after 1, 3, 6, and 15 cycles of the w-d test. The significant growth of cementitious products with the plenty presence of ettringite was detected for both samples with and without NRL at the third cycle compared to those of samples at the first cycle while microcracks were rarely detected in these initial cycles. This confirmed that the strength gain and water absorption reduction of samples during initial w-d cycles is due to the development of cementitious products with the support of temperature and water via w-d cycles. Beyond the optimum w-d cycle of 3 cycles, besides the reduction of cementitious products, the microcappearedearded and then propagated and extended to macrocracks, resulting in the weakening and strength loss of samples.

For the cement-NRL stabilized samples, it is clear that the number of cracks detected in the stabilized samples with NRL (at 3% of r/c ratio) (Figure 5.11c) is significantly lower than in the stabilized samples without NRL (at 0% of r/c ratio) (Figure 5.11a). Furthermore, pores and cracks of cement-NRL stabilized samples were infiltrated by NRL films. NRL films act as bridges to fill the pore space, micro-, and macrocracks, leading to the reduction of void ratio and increase of interparticle bonding strength inside the sample structure (Figure 5.10, 5.11d). As a result, the durability against wetting-drying cycles of cement-NRL stabilized samples was improved. In other words, NRL additive could change the microstructure of cement stabilized SS:LS and RCA:LS blends into a better structure and led to higher UCS_{w-d} and lower weight loss and water absorption.



(a) Cement stabilized SS:LS=70:30 (b) Cement-NRL stabilized SS:LS=70:30

Figure 5.10 SEM images of cement-NRL stabilized SS:LS=70:30 at (a) r/c ratio = 0% and (b) r/c ratio = 3% at 1st, 3rd, 6th, and 15th cycles.

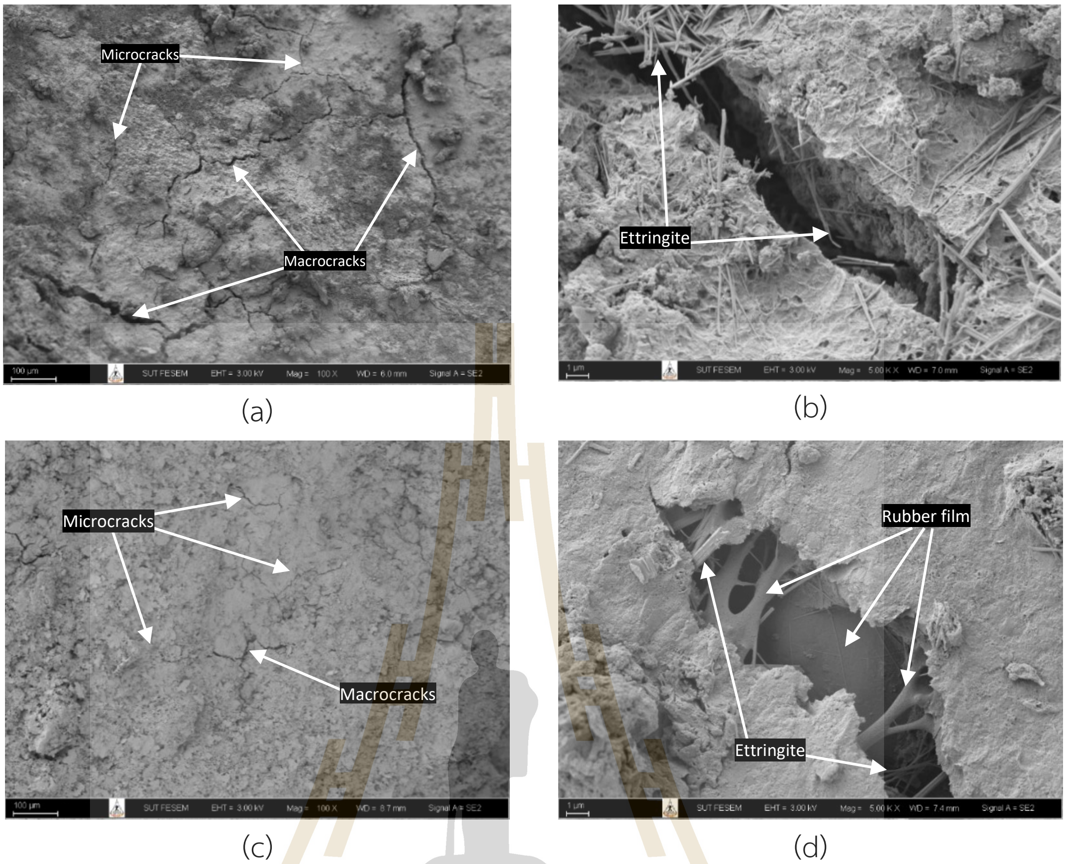


Figure 5.11 SEM images of cement-NRL stabilized RCA:LS = 70:30 at (a, b) r/c ratio = 0% and (c, d) r/c ratio = 5% after 15 number of w-d cycles.

5.4 Conclusions

This study investigated the influence of NRL additive on the durability against wetting-drying cycles of cement stabilized lateritic soil and recycled materials (SS/RCA) blends. 70% and 50% of SS/RCA were replaced for lateritic soil to create four blends including SS:LS=70:30, SS:LS=50:50, RCA:LS=70:30, and RCA:LS=50:50. 5% cement content by weight was used for all studied blends. Dry NRL to cement (r/c ratio) of 0%, 3%, and 5% was designed to investigate the influence of NRL additive on the durability of cement stabilized SS:LS and RCA:LS blends. The UCS, weight loss, water absorption, and microstructural change were considered as the results of the wetting-drying test. The following conclusion can be drawn:

1. The UCS_{w-d} development with an increase in the number of wetting-drying cycles was observed for all samples, up to 3 cycles and then decreased beyond

3 cycles. UCS_{w-d} of cement-NRL SS:LS=70:30 and RCA:LS=70:30 was found to be higher than that of cement-NRL stabilized SS:LS=50:50 and RCA:LS=50:50, respectively, while cement-NRL stabilized of SS:LS blends produced higher UCS_{w-d} than cement-NRL stabilized RCA:LS blends. At different r/c ratios, cement-NRL stabilized SS:LS blends with r/c ratio of 3% expressed the highest value of UCS_{w-d} while the highest UCS_{w-d} value of cement-NRL stabilized RCA:LS blends was found at r/c ratio of 5%.

2. Samples with NRL produced higher UCS and UCS_{w-d} and expressed lower weight loss and water absorption than samples without NRL during the wet-dry cycles test process. The NRL addition could improve the crack resistance of cement-NRL stabilized samples under the effect of wetting-drying cycles, leading to fewer cracks observed in cement-NRL samples compared to cement stabilized samples. This is because the formation of NRL films fills up the pore spaces and microcracks to reduce the porosity and therefore decrease the water absorption of cement-NRL stabilized samples. In addition, NRL films also increase the interparticle bond strength and contribute to a stronger structure, resulting in a lower percentage of weight loss over the w-d cycles.
3. The UCS_{w-d} development of cement-NRL stabilized samples occur simultaneously with the growth of cementitious products during the w-d process. The scanning electron microscope results showed that the significant growth of cementitious products was detected for both samples with and without NRL at the third cycle compared to those of samples at the first cycle while microcracks were rarely detected in these initial cycles. After 3 cycles, the decrease of cementitious products and increase of microcracks and thereby macrocracks caused the reduction in UCS_{w-d} of cement-NRL stabilized samples. The presence of NRL films was found in pores and cracks of cement-NRL stabilized structure decreased the void ratio and enhanced the interparticle bonding strength, leading to higher strength, and a lower percentage of weight loss and water absorption of cement-NRL stabilized samples than those of cement stabilized samples.

The research outcomes demonstrated that NRL additive could be used in the pavement base application to enhance the durability of cement stabilized recycled materials and lateritic soil, which improves the service of base course and thereby pavement under the effect of wetting-drying cycles.

5.5 References

ACI 230. (2009). Report on Soil Cement. *American Concrete Institute, Farmington Hills, MI*.

ASTM-C127-15. (2015). Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate. *West Conshohocken, PA*. Doi: 10.1520/C0127-15

ASTM-C131/C131M-14. (2014). Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine. *West Conshohocken, PA*. Doi: 10.1520/c0131

ASTM-D422-63. (2007). Standard Test Method for Particle-Size Analysis of Soils. *West Conshohocken, PA*. Doi: 10.1520/d0422-63r07

ASTM-D559-03. (2003). Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures. *West Conshohocken, PA*. Doi: 10.1520/d0559-03

ASTM-D1557-09. (2009). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3(2,700 kN-m/m3)). *West Conshohocken, PA*. Doi: 10.1520/d1557-09

ASTM-D1557-12. (2012). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3 (2,700 kN-m/m^3)). *West Conshohocken, PA: ASTM.* .

ASTM-D1633-17. (2017). Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders. *West Conshohocken, PA: ASTM.*

ASTM-D1883-07. (2007). Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils. *West Conshohocken, PA*. Doi: 10.1520/d1883-07e02

ASTM-D2487-06. (2006). Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). *West Conshohocken, PA*. Doi: 10.1520/d2487-06e01

ASTM-D4318-05. (2005). Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. *West Conshohocken, PA*. Doi: 10.1520/d4318-05

ASTM-D4791-99. (1999). Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate. *West Conshohocken, PA*.

Baghini, M. S., Ismail, A., Naseralavi, S. S., & Firoozi, A. A. (2016). Performance evaluation of road base stabilized with styrene–butadiene copolymer latex and Portland cement. *International Journal of Pavement Research and Technology, 9*(4), 321-336. Doi: 10.1016/j.ijprt.2016.08.006

Barišić, I., Dimter, S., & Rukavina, T. (2015). Elastic properties of cement-stabilized mixes with steel slag. *International Journal of Pavement Engineering, 17*(9), 753-762. Doi: 10.1080/10298436.2015.1019496

BERR. (2008). Strategy for sustainable construction. *London: Department for Business, Enterprise and Regulatory Reform, HM Government.*

Biswal, D. R., Sahoo, U. C., & Dash, S. R. (2018). Mechanical characteristics of cement stabilized granular lateritic soils for use as structural layer of pavement. *Road Materials and Pavement Design, 21*(5), 1201-1223. Doi: 10.1080/14680629.2018.1545687

Brue, F., Davy, C. A., Skoczylas, F., Burlion, N., & Bourbon, X. (2012). Effect of temperature on the water retention properties of two high performance concretes. *Cement and Concrete Research, 42*(2), 384-396. Doi: 10.1016/j.cemconres.2011.11.005

Buritatun, A., Suddeepong, A., Horpibulsuk, S., Udomchai, A., Arulrajah, A., Mohammadinia, A., . . . Hoy, M. (2022a). Improvement of Tensile Properties of Cement-Stabilized Soil Using Natural Rubber Latex. *Journal of Materials in Civil Engineering, 34*(4). Doi: 10.1061/(ASCE)MT.1943-5533.0004173

Buritatun, A., Takaikaew, T., Horpibulsuk, S., Udomchai, A., Hoy, M., Vichitcholchai, N., & Arulrajah, A. (2020). Mechanical Strength Improvement of Cement-Stabilized

Soil Using Natural Rubber Latex for Pavement Base Applications. *Materials in Civil Engineering, 32*(12). Doi: 10.1061/(ASCE)MT.1943-5533.0003471

Busari, A., Adeyanju, E., Loto, T., & Ademola, D. (2019). Recycled Aggregate in Pavement Construction: Review of Literatures. *Journal of Physics: Conference Series, 1378*(2). Doi: 10.1088/1742-6596/1378/2/022026

Cuisinier, O., & Masrouri, F. (2020). Impact of wetting/drying cycles on the hydromechanical behaviour of a treated soil. *E3S Web of Conferences, 195*. Doi: 10.1051/e3sconf/202019506008

DCLG. (2006). Builidng A greener future: Towards Zero Carbon Development. *Department for Communities and Local Government*.

DH-S204/2556. (2013). Standard for highway construction (Soil Cement Base), Department of Highways, Bangkok, Thailand In.

Donrak, J., Horpibulsuk, S., Arulrajah, A., Kou, H.-l., Chinkulkijniwat, A., & Hoy, M. (2018). Wetting-drying cycles durability of cement stabilised marginal lateritic soil/melamine debris blends for pavement applications. *Road Materials and Pavement Design, 21*(2), 500-518. Doi: 10.1080/14680629.2018.1506816

Drouet, E., Poyet, S., & Torrenti, J.-M. (2015). Temperature influence on water transport in hardened cement pastes. *Cement and Concrete Research, 76*, 37-50. Doi: 10.1016/j.cemconres.2015.05.002

Du, Y. J., Bo, Y. L., Jin, F., & Liu, C. Y. (2016). Durability of reactive magnesia-activated slag-stabilized low plasticity clay subjected to drying–wetting cycle. *European Journal of Environmental and Civil Engineering, 20*(2), 215-230. Doi: 10.1080/ 19648189.2015.1030088

Du, Y. J., Jiang, N. J., Shen, S. L., & Jin, F. (2012). Experimental investigation of influence of acid rain on leaching and hydraulic characteristics of cement-based solidified/stabilized lead contaminated clay. *J Hazard Mater, 225-226*, 195-201. Doi: 10.1016/j.jhazmat.2012.04.072

Dv, N., Hoy, M., Karntatam, K., Arulrajah, A., & Horpibulsuk, J. (2022). Cement – natural rubber latex stabilised recycled concrete aggregate as a pavement base material. *Road Materials and Pavement Design*, 1-15. Doi: 10.1080/14680629. 2022.2072755

Estabragh, A. R., Beytolahpour, I., & Javadi, A. A. (2011). Effect of Resin on the Strength of Soil-Cement Mixture. *Materials in Civil Engineering, 23*(7), 969-976. Doi: 10.1061/(ASCE)MT.1943-5533.0000252

Horpibulsuk, S., Katkan, W., Sirilerdwattana, W., & Rachan, R. (2006). Strength development in cement stabilized low plasticity and coarse grained soils: Laboratory and field study. *Soils and Foundations, 46*(3).

Horpibulsuk, S., Rachan, R., Chinkulkijniwat, A., Raksachon, Y., & Suddeepong, A. (2010). Analysis of strength development in cement-stabilized silty clay from microstructural considerations. *Construction and Building Materials, 24*, 2011-2021.

Hoy, M., Rachan, R., Horpibulsuk, S., Arulrajah, A., & Mirzababaei, M. (2017). Effect of wetting–drying cycles on compressive strength and microstructure of recycled asphalt pavement – Fly ash geopolymer. *Construction and Building Materials, 144*, 624-634. Doi: 10.1016/j.conbuildmat.2017.03.243

Huang, Y., Bird, R. N., & Heidrich, O. (2007). A review of the use of recycled solid waste materials in asphalt pavements. *Resources, Conservation and Recycling, 52*(1), 58-73. Doi: 10.1016/j.resconrec.2007.02.002

James, J., Sivapriya, S. V., Ali, S., Madhu, T. R., & Singh, B. (2021). Wetting and Drying Resistance of Lime-Stabilized Expansive Soils Modified with Nano-Alumina. *Elektronički časopis građevinskog fakulteta Osijek, 12*(22), 70-80. Doi: 10.13167/2021.22.6

Jooss, M., & Reinhardt, H. W. (2002). Permeability and diffusivity of concrete as function of temperature. *Cement and Concrete Research, 32*(9), 1497-1504. Doi: 10.1016/S0008-8846(02)00812-8

Jose, A., & Kasthurba, A. K. (2020). Laterite soil-cement blocks modified using natural rubber latex: Assessment of its properties and performance. *Construction and Building Materials*.

Khoury, N., & Zaman, M. M. (2007). Durability of stabilized base courses subjected to wet–dry cycles. *International Journal of Pavement Engineering, 8*(4), 265-276. Doi: 10.1080/10298430701342874

Li, Q., & Hu, J. (2020). Mechanical and Durability Properties of Cement-Stabilized Recycled Concrete Aggregate. *Sustainability, 12*(18). Doi: 10.3390/su12187380

Little DN, & S., N. (2009). *Recommended Practice for Stabilization of Sulfate-Rich Subgrade Soils*: Washington, DC: National Highway Cooperative Research Program, Transportation Research Board of National Academics.

Muhammad, B., & Ismail, M. (2012). Performance of natural rubber latex modified concrete in acidic and sulfated environments. *Cement and Concrete Research, 31*, 129-134. Doi: 10.1016/j.conbuildmat.2011.12.099

Pereira, P. M., & Vieira, C. S. (2022). A Literature Review on the Use of Recycled Construction and Demolition Materials in Unbound Pavement Applications. *Sustainability, 14*(21). Doi: 10.3390/su142113918

Portland Cement Association. (1992). Soil-cement laboratory handbook. *Portland Cement Association*.

Salehi, S., Arashpour, M., Kodikara, J., & Guppy, R. (2021). Sustainable pavement construction: A systematic literature review of environmental and economic analysis of recycled materials. *Journal of Cleaner Production, 313*. Doi: 10.1016/j.jclepro.2021.127936

Shen, S.-L., Han, J., & Du, Y. (2008). Deep Mixing Induced Property Changes in Surrounding Sensitive Marine Clays. *Journal of Geotechnical and Geoenvironmental Engineering - J GEOTECH GEOENVIRON ENG, 134*. Doi: 10.1061/(ASCE)1090-0241(2008)134:6(845)

Shihata, S. A., & Baghdadi, Z. A. (2001). Long-term strength and durability of soil cement. *Journal of Materials in Civil Engineering, 13*(3), 161-165. Doi: 10.1061/(ASCE) 0899-1561(2001)13:3(161)

Sivapullaiah, P. V., & Moghal, A. A. B. (2011). Role of Gypsum in the Strength Development of Fly Ashes with Lime. *Journal of Materials in Civil Engineering, 23*(2), 197-206. Doi: 10.1061/(asce)mt.1943-5533.0000158

Soldo, A., & Miletic, M. (2022). Durability against Wetting-Drying Cycles of Sustainable Biopolymer-Treated Soil. *Polymers (Basel), 14*(19). Doi: 10.3390/polym 14194247

Sudla, P., Donrak, J., Hoy, M., Horpibulsuk, S., Arulrajah, A., Rashid, A. S. A., . . . Samingthong, W. (2019). Laboratory Investigation of Cement-Stabilized Marginal Lateritic Soil by Crushed Slag–Fly Ash Replacement for Pavement Applications. *Materials in Civil Engineering, 32*(2).

Tingle, J. S., & Santoni, R. L. (2003). Stabilization of Clay Soils with Nontraditional Additives. *Transportation research board, 1819*(1). Doi: 10.3141/1819b-10

Tran, N. Q., Hoy, M., Suddeepong, A., Horpibulsuk, S., Kantathum, K., & Arulrajah, A. (2022). Improved mechanical and microstructure of cement-stabilized lateritic soil using recycled materials replacement and natural rubber latex for pavement applications. *Construction and Building Materials, 347*. Doi: 10.1016/j.conbuildmat.2022.128547

Vo, M. L., & Plank, J. (2018). Evaluation of natural rubber latex as film forming additive in cementitious mortar. *Construction and Building Materials, 169*, 93-99. Doi: 10.1016/j.conbuildmat.2017.12.098

Walker, P., & Stace, T. (1997). Properties of some cement stabilised compressed earth blocks and mortars. *Materials and Structures, 30*(9), 545-551. Doi: 10.1007/BF02486398

Wen, Y., Wang, Y., Zhao, K., & Sumalee, A. (2017). The use of natural rubber latex as a renewable and sustainable modifier of asphalt binder. *International Journal of Pavement Engineering, 18*(6), 547-559. Doi: 10.1080/10298436.2015.1095913

Xing, H., Yang, X., Xu, C., & Ye, G. (2009). Strength characteristics and mechanisms of salt-rich soil–cement. *Engineering Geology - ENG GEOL, 103*, 33-38. Doi: 10.1016/j.enggeo.2008.07.011

Xiong, F., Xing, H., & Li, H. (2019). Experimental study on the effects of multiple corrosive ion coexistence on soil-cement characteristics. *Soils and Foundations, 59*(2), 398-406. Doi: 10.1016/j.sandf.2018.12.001

Yaowarat, T., Horpibulsuk, S., Arulrajah, A., Maghool, F., Mirzababaei, M., Rashid, A. S. A., & Chinkulkijniwat, A. (2020). Cement stabilization of recycled concrete aggregate modified with polyvinyl alcohol. *International Journal of Pavement Engineering*. Doi: 10.1080/10298436.2020.1746311

Yaowarat, T., Suddeepong, A., Hoy, M., Horpibulsuk, S., Takaikaew, T., Vichitcholchai, N., . . . Chinkulkijniwat, A. (2021). Improvement of flexural strength of concrete pavements using natural rubber latex. *Construction and Building Materials, 282*. Doi: 10.1016/j.conbuildmat.2021.122704

Yaowarat, T., Sudsaynate, W., Horpibulsuk, S., Chinkulkijniwat, A., Arulrajah, A., & Horpibulsuk, J. (2021). Mechanical properties of fly ash–asphalt emulsion geopolymer stabilized crushed rock for Sustainable pavement base. *Journal of Materials in Civil Engineering, 33*(9), 04021220.

Yarbaşı, N., Kalkan, E., & Akbulut, S. (2007). Modification of the geotechnical properties, as influenced by freeze–thaw, of granular soils with waste additives. *Cold Regions Science and Technology, 48*(1), 44-54. Doi: 10.1016/j.coldregions.2006.09.009

Zalnezhad, M., & Hesami, E. (2020). Effect of steel slag aggregate and bitumen emulsion types on the performance of microsurfacing mixture. *Journal of Traffic and Transportation Engineering (English Edition), 7*(2), 215-226. Doi: 10.1016/j.jtte.2018.12.005

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and conclusions

In recent decades, the tendential approach in construction is increasing the use of industrial and construction waste materials to contribute to the reduction of their environmental impact and to solve the scarcity of natural materials. This research was performed on the use of steel slag (SS) and recycled concrete aggregate (RCA) as the replaced materials for natural lateritic soil (LS) with the effort of motivating the application of waste materials in construction, especially in pavement construction. Furthermore, improvement techniques of cement and natural rubber latex stabilization were also included in this research to reduce the unfavorable properties and improve the performance of materials, which is the main objective of this research. To reach this objective, an laboratory investigation of cement-stabilized recycled materials and lateritic soil blends was conducted. SS/RCA-to-LS ratios of 70:30 and 50:50, 5% cement by weight of dry materials, and Dry NRL-to-cement ratios of 0%, 3%, 5%, 10%, and 15% were considered as influent factors that affect the mechanical and microstructure, fatigue properties, and durability against wetting-drying cycles of cement-stabilized lateritic soil.

The thesis comprises three major research objectives. The first is to investigate the influence of recycled materials replacement and NRL on the mechanical properties and microstructure of cement-stabilized lateritic soil for pavement applications. The compressive and tensile strengths were evaluated as the criteria to assess the suitable materials to be the pavement base materials. Microstructure and chemical components of cement-NRL stabilized recycled and lateritic soil blends were determined by microstructural analyses including scanning electron microscope and X-ray diffraction. The SS-to-LS ratio, RCA-to-LS ratio, and r/c ratio were the influent factors that affect the microstructural and properties change of cement-NRL stabilized SS:LS and RCA:LS blends. Secondly, the influence of natural rubber latex on the resilient modulus and fatigue properties of cement-stabilized SS:LS and RCA:LS blends at different recycled materials replacement ratios were evaluated. Finally, durability against the wetting-drying cycles of cement-NRL stabilized recycled materials and lateritic soil blends were performed under the effect of recycled materials replacement and NRL contents (r/c ratios). The unconfined compressive strength after target cycles, water absorption, weight loss, and microstructural change of cement-NRL stabilized recycled materials and lateritic soil samples were considered as the results of this stage. The conclusions can be drawn as follow:

Chapter 3: Improved mechanical and microstructure of cement-stabilized lateritic soil using recycled materials replacement and natural rubber latex for pavement applications.

This research aims to study the influence of NRL on the strength development of cement-stabilized lateritic soil (LS) and recycled aggregate blends as a sustainable pavement base. The r/ c ratio was found to be a significant effect on the compactability, unconfined compressive strength (UCS), and indirect tensile (ITS) of cement-stabilized SS:LS and RCA:LS blends. The microstructural analyses using scanning electron microscopy and X-ray diffraction indicated that the degree of cement hydration of cement-NRL stabilized SS/RCA:LS blends decreased with increasing NRL content due to the retardation of thicker NRL films. However, at the optimum r/c ratio, the coexistence between cement hydration products and NRL films can reduce the pore space and enhance the interparticle bond strength, resulting in UCS and ITS development of cement-NRL stabilized blends. Although the optimum r/c ratio indicating the maximum UCS and ITS of cement-NRL stabilized SS:LS and RCA:LS samples were found to be different, the percent improvement by NRL is practically the same. The r/c ratio is a dominant factor affecting the interparticle bond strength, hence the relationship between UCS and ITS was developed, which is cost-effective and time-saving for geotechnical and pavement engineering design.

Chapter 4: Improved fatigue properties of cement-stabilized recycled materials-lateritic soil using natural rubber latex for sustainable pavement applications.

This study investigates the role of a new recycled pavement material and natural rubber latex (NRL), in improving the resilient and fatigue performances of cement-stabilized recycled materials and lateritic soil (LS) blends under traffic loads. The results indicated that mechanical strength properties namely unconfined compressive strength (UCS) and indirect tensile test (ITS), as well as fatigue properties namely indirect tensile resilient modulus (IT M_r) and indirect tensile fatigue (ITF) were enhanced with the NRL additive. Beyond the optimum r/c ratio, the excessive amount of NRL generated thick NRL films and retarded the cement hydration products, resulting in low strength and performance improvement. The r/c ratios of 3% and 5% were found to be the optimum r/c ratios for cement-NRL stabilized SS:LS and RCA:LS blends, respectively. The brittleness and permanent deformation of cement-stabilized SS/RCA:LS blends were significantly improved by the NRL additive. The superior mechanical and physical properties of SS and RCA were also attributed to the enhancement of fatigue characteristics of the cement-NRL stabilized blends. Finally, the mechanistic and fatigue models of cement- and cement-NRL stabilized soil with recycled material replacements were proposed, which are important for pavement designers and engineers when using a mechanistic-empirical pavement design approach.

Chapter 5: Durability against wetting-drying cycles of cement-stabilized recycled materials and lateritic soil blends using natural rubber latex for pavement applications

An investigation was conducted in this research to assess the role of natural rubber latex (NRL) in improving the durability of cement-stabilized lateritic soil and recycled materials blends against wetting-drying cycles. The unconfined compressive strength after target wetting-drying cycles (UCS_{w-d}), weight loss, water absorption, and microstructural change were considered as the results of the w-d cycles test to evaluate the influence of NRL on the durability of cement stabilized SS:LS and RCA:LS blends. The results indicated that the presence of NRL films infiltrates pores and cracks of cement-stabilized structures, resulting in increased UCS_{w-d} and decreased weight loss and water absorption. It is noted that the UCS of cement-NRL stabilized studied blends increase with the increase of initial w-d cycles, up to 3 cycles prior to a decrease after that. The scanning electron microscope (SEM) results showed that plenty of hydration products were detected in the samples at the third cycle. However, hydration products gradually decreased and micro- and macro-cracks increasingly appeared with the increase of w-d cycles after 3 cycles. These confirmed the variation of UCS, weight loss, and water absorption results during the w-d cycles test.

6.2 Recommendation for future works

The result of this research is a demonstration of the effective usage of natural rubber latex and recycled materials in sustainable pavement applications. However, to intensify the reliability of the NRL and recycled materials applications, several concerned works related to pavement base performance should be continuously studied:

- NRL has demonstrated its effectiveness in improving the performance of cement-stabilized SS/RCA and LS blends as pavement materials, other recycled materials such as reclaimed asphalt pavement and crushed brick should be considered for further study.
- Mechanical properties including compressive strength and flexural strength as well as durability against wetting-drying cycles and freeze-thaw cycles, and thermal testing should be comprehensively investigated for practical applications of cement-NRL stabilization.
- In this study, the durability against wetting-drying cycles was investigated on only unconfined compressive strength. The influence of wet-dry cycles on tensile strength under static and dynamic loading conditions of cement-NRL stabilized soil should be considered for further work.
- This finding demonstrated the effectiveness of NRL in improving the fatigue properties of cement-stabilized studied materials under indirect cyclic loading. The behavior including resilient modulus and fatigue life of cement-NRL stabilized materials under repeated loading triaxial condition is necessary to investigate for further reliability of research.
- The mechanistic test results in this research are essential for predicting the fatigue cracking life of the cement-NRL stabilized recycled aggregates based on the

mechanistic-empirical (M-E) design method. Therefore, a numerical analysis based on the present experimental results is recommended for future studies to develop the distress model, and to predict the fatigue cracking life of the pavement structure when using cement-NRL stabilized recycled aggregates as the base materials.

- Environmental impact and economic consideration of road construction projects as well as recycled materials applications should be evaluated.

APPENDIX A

PUBLICATIONS

List of publications

INTERNATIONAL JOURNAL PAPERS

Ngoc Quynh Tran, Menglim Hoy, Apichat Suddeepong, Suksun Horpibulsuk, Karn Kantathum, Arul Arulrajah (2022). "**Improved mechanical and microstructure of cement-stabilized lateritic soil using recycled materials replacement and natural rubber latex for pavement applications**". Journal of Construction and Building Materials.

DOI: https://doi.org/10.1016/j.conbuildmat.2022.128547

Menglim Hoy, Ngoc Quynh Tran, Apichat Suddeepong, Suksun Horpibulsuk, Manlika Mobkrathok, Avirut Chinkulkijniwat, Arul Arulrajah (2023). "**Improved fatigue properties of cement-stabilized recycled materials – Lateritic soil using natural rubber latex for sustainable pavement applications**". Journal of Transportation Geotechnics.

DOI: https://doi.org/10.1016/j.trgeo.2023.100959

Construction and Building Materials 347 (2022) 128547

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Improved mechanical and microstructure of cement-stabilized lateritic soil using recycled materials replacement and natural rubber latex for pavement applications

Ngoc Quynh Tran [a,b], Menglim Hoy [a,b,*], Apichat Suddeepong [b,c], Suksun Horpibulsuk [a,b,c,d,*], Karn Kantathum [b], Arul Arulrajah [e]

[a] School of Civil Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
[b] Center of Excellence in Innovation for Sustainable Infrastructure Development, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
[c] School of Civil and Infrastructure Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
[d] Academy of Science, The Royal Society of Thailand, Bangkok 10300, Thailand
[e] Department of Civil and Construction Engineering, Swinburne University of Technology, Melbourne, Australia

ARTICLE INFO

Keywords:
Natural rubber latex
Pavement base materials
Compressive strength
Tensile strength
Microstructure
Soil-cement
Ground improvement
Pavement geotechnics

ABSTRACT

Soil replacement with medium-graded waste materials is an effective means to improve the physical properties of marginal soil prior to cement stabilization and to minimize the input of cement at the target mechanical properties. Natural rubber latex possesses superior elastic properties, which can improve the fatigue properties of cement stabilized material. This research aims to study the influence of NRL on the strength development of cement stabilized lateritic soil (LS) and recycled aggregate blends as a sustainable pavement base. The steel slag (SS) and recycled concrete aggregate (RCA) replacement ratios of 50% and 70% were studied. The cement content of 5% by weight and dry rubber to cement (r/c) ratios of 0%, 3%, 5%, and 10% were investigated. The r/c ratio was found to be a significant effect on the compactability, unconfined compressive strength (UCS), and indirect tensile (ITS) of cement stabilized SS:LS and RCA:LS blends. The microstructural analyses using scanning electron microscopy and X-ray diffraction indicated that the degree of cement hydration of cement-NRL stabilized SS/RCA:LS blends decreased with increasing NRL content due to the retardation of thicker NRL films. However, at the optimum r/c ratio, the coexistence between cement hydration products and NRL films can reduce the pore space and enhance the interparticle bond strength, resulting in UCS and ITS development of cement-NRL stabilized blends. Although the optimum r/c ratio indicating the maximum UCS and ITS of cement-NRL stabilized SS:LS and RCA:LS sample were found to be different, the percent improvement by NRL is practically the same. The r/c ratio is a dominant factor affecting the interparticle bond strength, hence the relationship between UCS and ITS was developed, which is cost-effective and time-saving for geotechnical and pavement engineering design. The result from this research is a demonstration of the effective usage of natural rubber latex and recycled materials in sustainable pavement applications.

1. Introduction

The pavement structure, comprising base and subbase layers beneath the surface layer (i.e., concrete or asphalt pavement) is normally built from natural aggregates such as natural quarry and granular aggregate materials. Lateritic soil (LS), which is abundantly available in the tropical countries, is employed as an alternative pavement base/subbase material for the purpose of reducing cost of road construction [1,2]. However, some natural LS have unfavorable characteristics when used as a road construction material. The mineralogical and structural alteration of LS is influenced by the duration of exposure to weathering and the subjected load, which leads to a change in engineering properties. A deep understanding of the structure and engineering behavior of LS is important for the usage of this material in highway construction.

* Corresponding authors at: School of Civil Engineering, Suranaree University of Technology, 111 University Avenue, Muang District, Nakhon Ratchasima 30000, Thailand.
E-mail addresses: ttnquynh@hueuni.edu.vn (N.Q. Tran), menglim@g.sut.ac.th (M. Hoy), suddeepong@g.sut.ac.th (A. Suddeepong), suksun@g.sut.ac.th (S. Horpibulsuk), aarulrajah@swin.edu.au (A. Arulrajah).

https://doi.org/10.1016/j.conbuildmat.2022.128547
Received 7 February 2022; Received in revised form 11 July 2022; Accepted 19 July 2022
Available online 28 July 2022

The lessons learned from the previous research and practice demonstrated that the damage of LS base was due to the deterioration of the soil aggregate and its swelling behavior when subjected to the intense rainfall [3,4]. In addition, the longitudinal and transverse cracks of the pavement occurred when the tensile strength of the lateritic soil cannot resist the high volume of traffic load [5,6]. Otálvaro, Neto and Caicedo [7] investigated the compressibility and microstructure of compacted lateritic soil for pavement application and indicated that the bimodal and grain size distribution were changed during compression and more than 50 % of the broken soil aggregates caused the collapse of lateritic soil pavement.

Some researchers have demonstrated that lateritic soils sometimes have unfavorable physical and mechanical properties such as high plasticity, substandard gradation, and low California bearing ratio (CBR), which do not always comply with the specifications for high volume roads designated by international or local road authorities [2,8–11]. As a result, improvement techniques have been applied for enhancing the quality of lateritic soils to achieve the required mechanical properties for pavement construction criteria. One of the cost-effective and widely used techniques is the soil replacement with chemical stabilization method. In chemical stabilization, the interlocking between fine and coarse particles is enhanced by mixing unfavorable soils with high-quality coarse materials having an appropriate grain size distribution. A blend of 50 %LS, 40 % quarry aggregate, and 10 % carbon black was reported to have the satisfied gradation and engineering properties for road base/subbase course [12]. The stabilizers including lime, fly-ash, and cement are commonly used in chemical stabilization method whilst Portland cement is preferred in most Southeast Asian countries because of the rapid improvement of mechanical properties at reasonable cost [13–15]. The hydration products are generated within the void space of material grains and enhance mechanical properties of cement stabilized aggregates [16,17]. The degree of improvement is affected by influential factors such as water/cement content, curing condition, and compaction effort [18].

Mengue et al. [19] indicated that 6 % to 9 % cement stabilized LS can be used as a pavement base as it satisfied the minimum strength requirement. In addition, remarkable shear strength improvement of cement stabilized LS was observed via triaxial loading test results. The effect of wetting–drying cycles on the durability of cement-LS mixture was investigated and found that the samples with 6 % cement content could resist against 15 wetting–drying cycles, while the samples with higher cement content up to 12 % can resist more cycles [20]. Joel and Agbede [13], and Consoli, Párraga Morales and Saldanha [21] studied the mechanical properties of cement stabilized LS/sand blend at different sand replacement ratios (0, 15, 30, 45, and 60 %) and cement contents (0, 3, 6, 9, and 12 %). The Atterberg limits, CBR, and UCS of the cement stabilized LS/sand blends were improved with the increase of sand replacement ratio and cement content. The 6 % cement and 45 % sand replacement ratio were found to be the optimum ingredient for soil–cement-sand mixture as a pavement base.

To preserve natural resources and reduce the environmental burden, many researchers used the construction and demolition wastes including recycled concrete aggregate (RCA), recycled asphalt pavement (RAP), crushed brick (CB), and other industrial by-products including SS, plastic polyethylene terephthalate (PET), calcium carbide residue (CCR) instead of the natural aggregates for a sustainable pavement application [22–27]. Furthermore, several studies have reported that SS and RCA can be deployed in pavement applications because their mechanical characteristics are evaluated to be similar or even superior to natural materials [28–33]. The UCS of cement stabilized 15 %RCA-soil mixtures was reported to satisfy the minimum strength requirement as a subbase/subgrade for flexible and rigid pavement [31]. Sudla et al. [30,34] investigated the LS and crushed slag (CS) blends stabilized by cement and fly ash (FA) as a pavement base. The CS replacement was found to improve the gradation and the resistance against Los Angeles abrasion and the soaked CBR of the blend, while reduce its liquid limit and plasticity index. In addition, the durability of cement and fly ash stabilized LS and CS blend against the wetting–drying cycles were also improved.

Even with its undeniable efficiency, cement stabilized material displays a shortcoming of brittle behavior, especially under compressive and tensile stresses [19,20,35–38]. Pavement materials are commonly subjected to the tensile and flexural stresses caused by the wheel loads and the internal temperature. When the cement stabilized aggregate layers with low tensile and flexural strengths subject to these stresses, cracking takes place, which causes the reduction in the structural strength or the premature failure of the pavement. In addition, the water effortlessly enters the subgrade through the cracks, decreases the subgrade support and thereby hastens pavement deterioration. As a result, the service life of pavement structure is decreased.

Synthetic polymer additives including polyvinyl alcohol and asphalt emulsion were deployed to alleviate the limitations of cement-stabilized soils by enhancing the microstructure and mechanical properties of the mixtures. This leads to the improvement of serviceability and sustainability of road using cement-stabilized soil as a pavement material [39–44].

Natural rubber latex (NRL) is a natural polymer which has high elastic and tensile properties similar to synthetic polymer additives. Thailand is one of the largest producers of NRL worldwide. Besides exporting, the Thailand government also encourages research and development on using NRL in civil construction applications and especially in pavement applications as the road system in Thailand is rapidly growing. Indeed, NRL has been researched and proven to be effective in tensile and flexural strength improvement of cement mortar, cement paste, concrete, and cement-stabilized soils [14,40,45–47].

However, to the best of author's knowledge, the utilization of NRL as a polymer to improve the mechanical properties of cement stabilized lateritic soil with recycled aggregate replacement as pavement materials has not been studied. Using available in-situ LS in road construction can reduce the costs of transporting materials while the reuse of recycled aggregates can prevent the depletion of earth's natural resource and assist to offset environmental problem. For eco-friendly and cost-effective approach, this research attempts to ascertain the UCS and ITS of cement-NRL stabilized LS blended with SS and RCA as a sustainable pavement base material. Blending lateritic soil with SS and RCA can reduce fine contents and improve its particle contact strength. The cement content, dry rubber-to-cement (r/c) ratio, SS:LS ratio, and RCA:LS ratio were the influence factors investigated in this research. The microstructural analyses including scanning electron microscopy (SEM) and X-ray diffraction (XRD) were conducted to provide an insight into the influence factors on mechanical strength development. This research output will demonstrate the effective utilization of natural rubber latex and recycled materials for sustainable pavement technology.

2. Materials and methods

2.1. Materials

Original Portland cement was used in this research and its physical and mechanical properties are provided in Table 1. The natural rubber latex (NRL) obtained from the Rubber Authority of Thailand was used as a non-traditional additive. It was comprised of sodium dodecyl sulphate (SDS), zinc 2-mercaptobenzothiazole (ZMBT), zinc oxide, calcium carbonate. SDS was used as a surfactant to remove protein. ZMBT, zinc oxide, calcium carbonate, and sulphur substances can enhance the workability and properties of NRL. Table 2 shows the compositions of NRL; it was classified as the low dry rubber content (<31 %) [46].

Aggregates used this research included lateritic soil (LS), steel slag (SS), and recycled concrete aggregate (RCA). LS was collected from Nakhon Ratchasima province, Thailand, SS was obtained from Siam Steel Mill services Co., ltd., Chonburi province, Thailand, and RCA was from the demolished concrete structures. The grain size distribution and

Table 1
Physical and chemical properties of Portland cement.

Properties of Portland cement	Values
Workability properties	
Initial setting time	101 min
Final setting time	188 min
Unconfined Compressive Strength (UCS)	
7-days UCS	24.7 MPa
28-days UCS	32.6 MPa
Chemical compositions in percent	
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 2
Properties of Natural Rubber Latex (NRL).

Properties	Values
Total solid content, %wt	33.06
Dry rubber content, %wt	30.79
Sludge content, %wt	2.46
Coagulum content, %wt	0.024
Specific garvity, G_s	0.96
pH	8

Table 3
Engineering properties of SS, RCA and LS.

Properties	SS	RCA	LS	Standard for base materials (DH-S201/2544)	Standard for stabilization of base materials (DH-S204/2532)
	Values				
Largest particle size, mm	25	25	25	≤50	≤50
Los Angeles abrasion, %	17.2	31	34	≤40	≤60
Liquid limit, %	–	–	21	≤25	≤40
Plastic limit, %	–	–	8	≤6	–
Plasticity index, %	–	–	14	≤6	≤15
Specific gravity	3.64	2.57	2.78	–	–
Maximum dry density, kg/m^3	2700	1960	2130	–	–
Optimum water content, %	6.04	12	8.07	–	–
California bearing ratio	58	43	18.16	≥80	–
Water absorption of coarse-grained (%)	1.21	3.2	5.95	–	–
Water absorption of fine-grained (%)	4.53	5.3	4.2	–	–

engineering properties of aggregates are summarized in Fig. 1 and Table 3, respectively, which were benchmarked with the national standards, Department of Highways (DOH), Thailand [48–51]. These national standards are adopted from the standard specification for materials for soil-aggregate subbase, base, and surface courses according to ASTM D 1241 [52], which is similar to AASHTO M 147–17 [53]. LS had high fine content and its index properties did not compliance with the specification of DOH, Thailand. Although the Los Angeles abrasion value of LS was within the requirements for base material specified by DOH, Thailand, its Los Angles abrasion and soaked CBR value were found to be low. Similar research works suggested that the LS with low Los Angles abrasion required to blend with high-quality coarse aggregates to minimize the deterioration of the soil aggregates when subjected to cyclic traffic loading [15,26,34,54]. Therefore, LS must be blended with RCA/LS to improve physical and mechanical properties prior to cement stabilization for pavement applications. Table 4 shows the chemical compositions of LS, SS, and RCA obtained from the X-ray fluorescence (XRF) analysis. The major components of LS were SiO_2 (75.51 %), Al_2O_3 (14.28 %), and Fe_2O_3 (6.64 %). The major components of SS and RCA were CaO, SiO_2, Al_2O_3, Fe_2O_3, and MgO. SS contained higher amount of Fe_2O_3 and MgO than RCA, while RCA had higher amount of CaO and SiO_2 than SS.

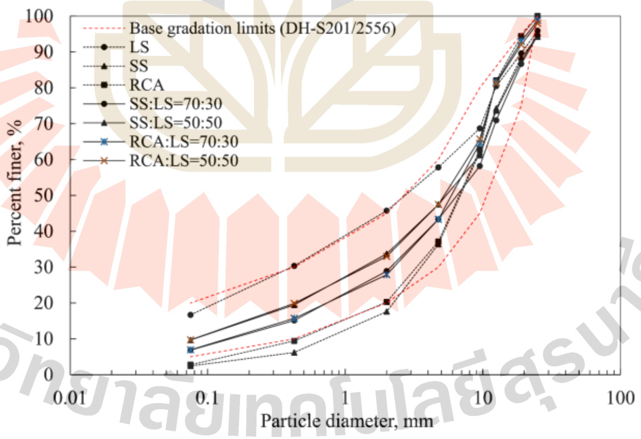


Fig. 1. Particle grain size distribution.

Table 4
Calcite and Quartz contents in cement-NRL stabilized samples at different r/c ratios.

Cement-NRL stabilized samples	r/c ratios, (%)	Calcite ($CaCO_3$), (%)	Quartz (SiO_2), (%)
SS:LS = 70:30	0	12.96	70.69
	3	10.99	69.65
	5	11.56	68.30
	10	12.67	65.29
	15	13.58	60.95
RCA:LS = 70:30	0	35.75	49.88
	3	32.32	49.65
	5	29.17	49.32
	10	31.59	50.10
	15	34.52	50.31

2.2. Experimental program

2.2.1. Mix design

This research aims to evaluate the effect of NRL and the recycled aggregates (SS and RCA) replacement on the UCS and indirect tensile strength (ITS) of the cement-NRL stabilized blends as pavement base courses. The cement stabilized SS:LS and cement stabilized RCA:LS were prepared as controlled materials. The cement-NRL stabilized SS:LS and cement-NRL stabilized RCA:LS were prepared at dry rubber to cement (r/c) ratios of 3 %, 5 %, 10 %, and 15 %. The SS and RCA replacement ratios were SS:LS = 70:30 and 50:50, and RCA:LS = 70:30 and 50:50. The gradation curves of each blend were also presented in Fig. 1. In this research, 5 % cement content by weight practically used in Thailand was selected [48]. The sample preparation was commenced by mixing recycled aggregates (SS or RCA) with LS and cement thoroughly. The mixtures were then mixed with water to produce the cement-stabilized SS:LS and RCA:LS samples and mixed with water-NRL to produce the cement-NRL stabilized SS:LS and RCA:LS samples. Table 5 summarizes the ingredient and name of the studied mix design in this study.

Table 5
The mix design in this study.

Mixture Ingredient	Mixture Name
Unstabilized SS:LS and RCA:LS mixtures for UCS test	
70 % SS + 30 % LS + Water	SS:LS = 70:30
50 % SS + 50 % LS + Water	SS:LS = 50:50
70 % RCA + 30 % LS + Water	RCA:LS = 70:30
50 % RCA + 50 % LS + Water	RCA:LS = 50:50
Cement- and Cement-NRL Stabilized SS:LS mixtures	
70 % SS + 30 % LS + 5 % Cement	SS:LS = 70:30, r/c = 0 %
50 % SS + 50 % LS + 5 % Cement	SS:LS = 50:50, r/c = 0 %
70 % SS + 30 % LS + 5 % Cement + 3 % Dry Rubber	SS:LS = 70:30, r/c = 3 %
50 % SS + 50 % LS + 5 % Cement + 3 % Dry Rubber	SS:LS = 50:50, r/c = 3 %
70 % SS + 30 % LS + 5 % Cement + 5 % Dry Rubber	SS:LS = 70:30, r/c = 5 %
50 % SS + 50 % LS + 5 % Cement + 5 % Dry Rubber	SS:LS = 50:50, r/c = 5 %
70 % SS + 30 % LS + 5 % Cement + 10 % Dry Rubber	SS:LS = 70:30, r/c = 10 %
50 % SS + 50 % LS + 5 % Cement + 10 % Dry Rubber	SS:LS = 50:50, r/c = 10 %
70 % SS + 30 % LS + 5 % Cement + 15 % Dry Rubber	SS:LS = 70:30, r/c = 15 %
50 % SS + 50 % LS + 5 % Cement + 15 % Dry Rubber	SS:LS = 50:50, r/c = 15 %
Cement- and Cement-NRL Stabilized RCA:LS mixtures	
70 % RCA + 30 % LS + 5 % Cement	RCA:LS = 70:30, r/c = 0 %
50 % RCA + 50 % LS + 5 % Cement	RCA:LS = 50:50, r/c = 0 %
70 % RCA + 30 % LS + 5 % Cement + 3 % Dry Rubber	RCA:LS = 70:30, r/c = 3 %
50 % RCA + 50 % LS + 5 % Cement + 3 % Dry Rubber	RCA:LS = 50:50, r/c = 3 %
70 % RCA + 30 % LS + 5 % Cement + 5 % Dry Rubber	RCA:LS = 70:30, r/c = 5 %
50 % RCA + 50 % LS + 5 % Cement + 5 % Dry Rubber	RCA:LS = 50:50, r/c = 5 %
70 % RCA + 30 % LS + 5 % Cement + 10 % Dry Rubber	RCA:LS = 70:30, r/c = 10 %
50 % RCA + 50 % LS + 5 % Cement + 10 % Dry Rubber	RCA:LS = 50:50, r/c = 10 %
70 % RCA + 30 % LS + 5 % Cement + 15 % Dry Rubber	RCA:LS = 70:30, r/c = 15 %
50 % RCA + 50 % LS + 5 % Cement + 15 % Dry Rubber	RCA:LS = 50:50, r/c = 15 %

Modified compaction test was performed based on ASTM D1557 [55] to obtain the maximum dry density (MDD) and optimum water content (OWC) of the studied blends. Thereafter, the samples prepared at the MDD and OWC were subjected to UCS test and ITS test. The unstabilized SS:LS blends and RCA:LS blends were also prepared and tested to evaluate the effect of cement on the UCS development.

2.2.2. Unconfined compressive strength (UCS)

UCS test was conducted in accordance with ASTM D1633 [56]. The mold with 101.60 mm in diameter and 116.8 mm in height was used to prepare samples. Samples were cured in the mold for 24 h before they were removed and wrapped by plastic films. They were then cured in a controlled temperature room at 25 ± 2 °C for 7- and 28 days. The UCS test was conducted with a vertical deformation rate of 1.0 mm per minute by using a compression machine. Three samples of each mixture were prepared and tested under the same condition to ensure the reliability of results.

2.2.3. Indirect tensile strength (ITS)

ITS test is the prescribed method to measure the tensile characteristic, which is related to cracking resistance of cement stabilized aggregates. ITS samples were prepared using a mold with internal diameter of 101.60 mm and height of 63.5 mm under the same designed mixtures and curing conditions as UCS test. Based on ASTM D6931 [57], the ITS test was also conducted on the compression test machine with a vertical deformation rate of one mm per minute.

For the mechanical properties tests of the studied mixtures, at least three samples were prepared and tested for each mixture under the same testing conditions in order to ensure the data consistency. The results were reported with a low mean standard deviation (SD/x < 10 %, where x is the mean strength value and SD is the standard deviation).

2.2.4. Microstructural analysis

SEM was performed to examine the growth of cementitious products in the samples. SEM samples were collected from broken fragments of the 28 days cured samples after UCS test. The liquid nitrogen was applied to immobilize the samples for about five minutes prior to evacuation at a pressure of 0.5 Pascal at −40 °C for five days. The samples were then coated with gold prior to SEM analysis.

For the XRD analysis, the fragments of 28 days cured samples were collected, pulverized and passed through a 0.75 mm sieve to obtain the powder samples. Thereafter, they were oven-dried at 110 °C for 24 h before being subjected to XRD analysis. The powder samples were placed onto the X-ray diffractometer, and the readings were recorded for 2θ angles from 10° to 60°, and at an angular speed of 2°/min with a step size of 0.02.

3. Results and discussion

3.1. Compaction characteristics

The compaction characteristics (MDD and OWC) of the unstabilized samples, cement stabilized SS:LS and RCA:LS, and cement-NRL stabilized SS:LS and RCA:LS with different SS/RCA:LS ratios and r/c ratios are illustrated in Fig. 2. For unstabilized samples, the 70SS:30LS blend had a higher MDD value than the 50SS:50LS blend whilst their OWC values were similar. Because the specific gravity of SS (G_s = 3.64) was higher than that of LS (G_s = 2.78), the MDD of SS:LS blends increased with the increased SS replacement. In contrast, the specific gravity of RCA (G_s = 2.57) was lower than that of LS. Hence, the 70RCA:30LS blend had lower MDD value than the 50RCA:50LS blend while the OWC of 70RCA:30LS blend was higher than that of 50RCA:50LS blend due to the higher water absorption of RCA. Moreover, the OWC value was more sensitive to the RCA replacement than the SS replacement.

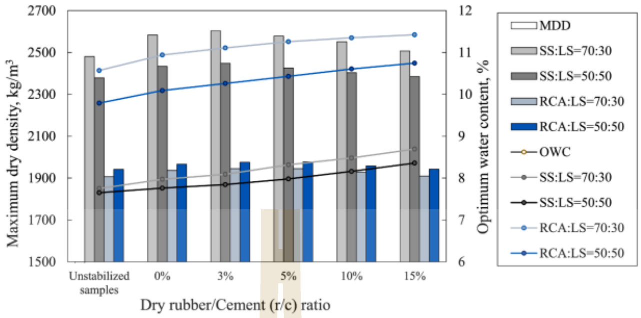


Fig. 2. The illustration of compaction characteristics of mixtures.

The compaction behavior of the cement stabilized SS:LS and the cement stabilized RCA:LS (at r/c = 0 %) was found to be similar to that of unstabilized samples while the MDD and OWC of the cement stabilized samples were higher. This is because more water is required for cement hydration and therefore it lubricates interparticle interaction between recycled aggregates and lateritic soils prior to the initial setting to develop the denser package and higher MDD. This result is in agreement with the previous finding [9,10,14].

The MDD and OWC values of cement-NRL stabilized SS:LS and RCA:LS samples at different r/c ratios are also demonstrated in Fig. 2. The MDD of cement-NRL stabilized SS:LS and RCA:LS samples increased with the increased r/c ratio and reached the maximum values prior to the decrease of MDD. While the OWC of these samples gradually increased with the increased r/c ratio. The r/c ratio of 3 % was found be optimum for cement-stabilized SS:LS samples at both SS:LS ratios of 70:30 and 50:50. Whereas the optimum r/c ratio for cement-stabilized RCA:LS samples at ratios of 70:30 and 50:50 was found to be the same at r/c ratio of 5 %. This implies that the influence of NRL can enhance the compactability of cement stabilized material and lead to an increase in MDD. However, beyond the optimum r/c ratio, the undue solid form of NRL causes the reduction in MDD of the mixtures. This is because the NRL substance coagulates the mixtures and separates solid particles to form loose aggregation. The similar results were found in previous research studies on NRL modified soil–cement stabilization [14,40,58].

The MDD of cement-NRL stabilized 70SS:30LS and 50SS:50LS samples was significantly higher than that of cement-NRL stabilized 70RCA:30LS and 50RCA:50LS samples at all r/c ratios. This is due to the specific gravity of the SS (G_s = 3.64) being higher than that of LS (G_s = 2.78) and RCA (G_s = 2.57). As a result, the higher SS and RCA replacement ratio contributed to the increase and the decrease in MDD of the SS:LS and RCA:LS blends, respectively, which has been previously reported by Sudla et al. [30]. On the other hand, the SS:LS blends had lower OWC than the RCA:LS blends because the SS had lower water absorption capacity than the RCA and the LS.

3.2. Unconfined compressive strength

Fig. 3 summaries the UCS of cement stabilized SS:LS and RCA:LS and cement-NRL stabilized SS:LS and RCA:LS samples at different SS/RCA: LS ratios with various r/c ratios. The UCS of unstabilized SS:LS blends

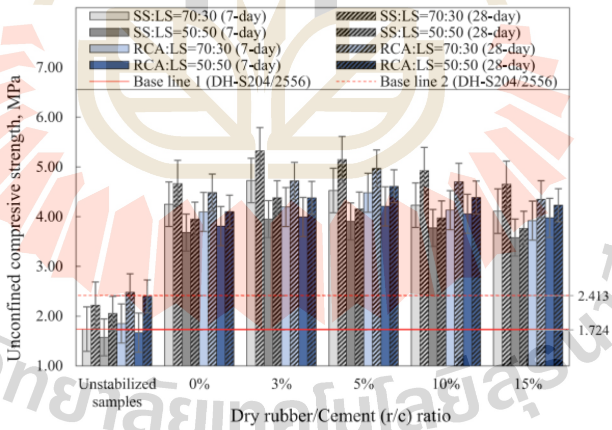


Fig. 3. Unconfined compressive strength of unstabilized samples, cement- and cement-NRL stabilized SS:LS and RCA:LS samples at various r/c ratios.

and RCA:LS blends were also presented to evaluate the effect of the cement stabilization. It is noteworthy that the UCS of both unstabilized blends increased with increasing the curing time. The 7- and 28-day UCS of pure LS was however found to be similar, which was 0.26 MPa and 0.28 MPa, respectively. This implied that unreacted cement particles in RCA and lime particles in SS could react with water and caused the UCS development over time. The UCS of unstabilized RCA:LS blends was higher than that of SS:LS blends at both 7 and 28 days of curing. This showed that the RCA had higher degree of chemical reaction, which could be attributed to the higher amount of CaO and SiO_2, detected by XRF analysis, of RCA when compared with SS.

The 7-day UCS values of all cement stabilized SS:LS and RCA:LS samples at all r/c ratios were significantly higher than those of the unstabilized samples and the minimum requirement for both low traffic volume road (7-day UCS $\geq$ 1.724 MPa) and high traffic volume road (7-day UCS $\geq$ 2.413 MPa) specified by DOH, Thailand [49]. This might be attributed to the cement hydration products and NRL films on the enhancement of interparticle bonding within the stabilized samples matrix.

At a particular type of recycled aggregate, the cement stabilized blends with higher replacement ratios had higher 7-day UCS than the cement stabilized LS. The 7-day UCS of cement stabilized 70SS:30LS sample was higher than that of cement stabilized 70RCA:30LS sample while the 7-day UCS values of cement stabilized 50SS:50LS and 50RCA:50LS were found to be similar. Sudla et al. [30] reported the low Los Angeles abrasion resistance of SS can enhance the engineering properties of SS and LS blends. In this research, the Los Angles abrasion of LS (34 %) was higher than RCA (31 %) and higher than SS (17.2 %), which means the mechanical strength of SS was better than RCA and LS. As a result, the cement stabilized SS:LS had higher UCS value than the cement stabilized RCA:LS at the same recycled aggregate replacement ratios (SS:LS = 70:30 and RCA:LS = 70:30). Moreover, at all recycled aggregate replacement ratios, the UCS of cement stabilized SS:LS and RCA:LS samples increased with longer curing period. These findings

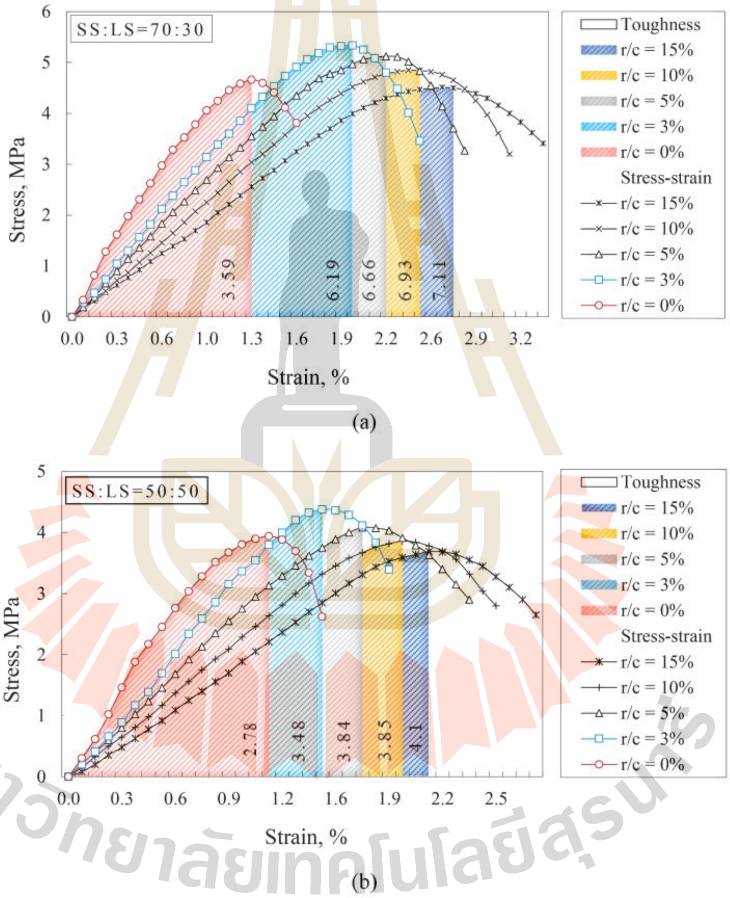


Fig. 4. Stress–strain curves of cement and cement-NRL stabilized SS:LS samples: (a) SS:LS = 70:30 and (b) SS:LS = 50:50.

were similar to the previous studies on the utilization of cement stabilized SS and RCA as pavement base/subbase materials in that the UCS of the stabilized LS increased with increasing the recycled aggregate content, cement content, and curing time [29,31].

The UCS values of cement-NRL stabilized SS:LS and RCA:LS depend upon its r/c ratios and curing time. The UCS development trends of cement-NRL stabilized SS:LS and RCA:LS were found to be similar; UCS increased with increasing the r/c ratio until the maximum value at the optimum r/c ratio and then declined with further increase in r/c ratio. At the optimum r/c ratios, the UCS values of both cement-NRL stabilized SS:LS and RCA:LS samples were higher than those of the cement-stabilized SS:LS and RCA:LS (r/c ratio = 0 %) samples. This confirms that the addition of NRL can enhance the cement stabilized SS/RCA and soil blends.

However, the optimum r/c ratio producing the maximum UCS of cement-NRL stabilized SS:LS and RCA:LS samples were found to be different. The highest UCS values of cement-NRL stabilized SS:LS and RCA:LS samples at all recycled aggregate replacement ratios cured for both 7 and 28 days were found at the optimum r/c ratio of 3 % and 5 %, respectively. At the optimum r/c ratio, the 7-day UCS of cement-NRL stabilized 70SS:30LS (r/c ratio = 3 %) and 70RCA:30LS (r/c ratio = 5 %) samples was approximately 12 % and 10.5 % higher than that cement stabilized 70SS:30LS and 70RCA:30LS samples, respectively. Meanwhile, at the optimum r/c ratio, the 7-day UCS of cement-NRL stabilized 50SS:50LS (r/c ratio = 3 %) and 50RCA:50LS (r/c ratio = 5 %) samples was about 9 % and 11 % higher than cement stabilized 50SS:50LS and 50RCA:50LS, respectively. It is therefore worthwhile mentioning that at optimum r/c ratio, the percent improvement by NRL is practically the same even with different in replacement ratios and replacement materials.

Figs. 4 and 5 demonstrate the stress and strain curves of cement- and cement-NRL stabilized SS:LS samples, and RCA:LS samples at age of 28 days, respectively. The UCS and ductility of both cement-NRL stabilized SS:LS and RCA:LS samples were found to be improved with the NRL

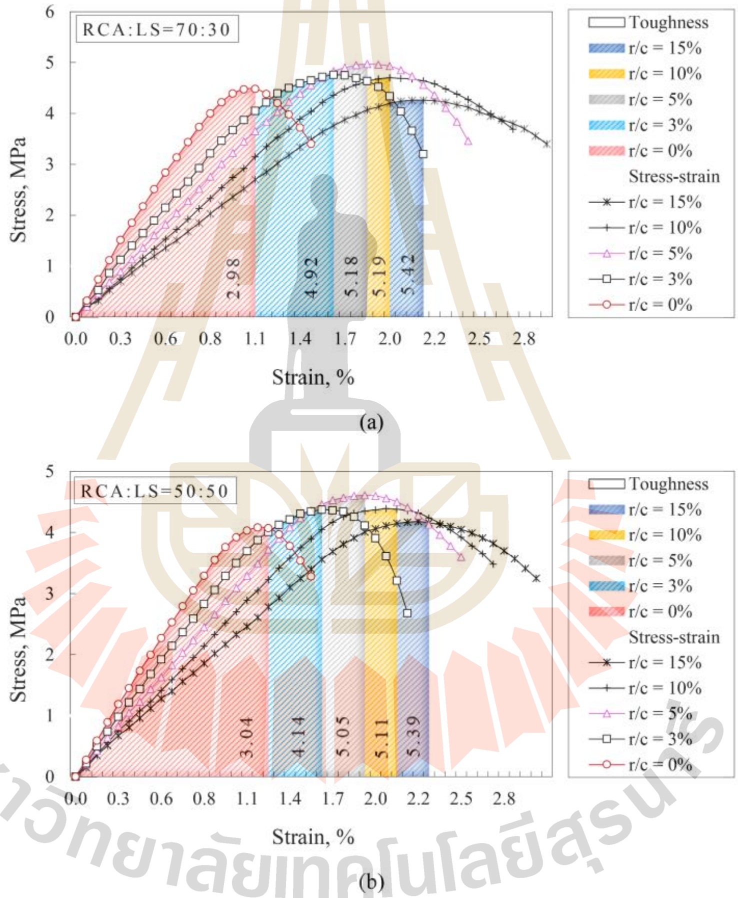


Fig. 5. Stress–strain curves of cement and cement-NRL stabilized RCA:LS samples: (a) RCA:LS = 70:30 and (b) RCA:LS = 50:50.

additive when compared with those of the corresponding cement stabilized samples (r/c ratio = 0 %). The higher strain at failure of all cement-NRL stabilized SS:LS samples and RCA:LS samples was found at the higher r/c ratio. This implied that the high elastic property of NRL additive played a significant role in improving the brittle behavior of cement stabilized samples. The toughness of the samples could be illustrated by the area under the stress–strain curve of the samples. It was clearly indicated that the cement-NRL stabilized samples exhibited higher toughness than the cement stabilized samples (without NRL additive); the toughness increased with the increased r/c ratio. This is a merit of cement-NRL stabilized recycled aggregate and soil blends as a pavement base subjected to cyclic loading of vehicles.

3.3. Indirect tensile strength

The ITS of cement stabilized SS:LS and RCA:LS samples and cement-NRL stabilized SS:LS and RCA:LS samples at different SS/RCA:LS ratios and various r/c ratios were evaluated and are shown in Fig. 6**a and 6b**. The 7- and 28-day ITS of pure LS was 0.11 MPa and 0.16 MPa, respectively. The ITS development pattern of cement stabilized SS:LS and RCA:LS samples and cement-NRL stabilized SS:LS and RCA:LS samples were found to be similar to the UCS development pattern. Indeed, the highest values of ITS were obtained at the optimum r/c ratios of 3 % and 5 % respectively for the cement-NRL stabilized SS:LS and cement-NRL stabilized RCA:LS samples. At the optimum r/c ratios, the values of ITS curing at 7 days of cement-NRL stabilized SS:LS and RCA:LS samples were approximately 10 % higher than those of cement stabilized SS:LS and RCA:LS samples. This confirms that the addition of NRL can also empower the tensile strength of the cement stabilized recycled aggregate and soil blends.

The cement-NRL stabilized samples with higher recycled aggregate replacement ratios (SS:LS = 70:30 and RCA:LS = 70:30) exhibited higher ITS values than the samples with lower replacement ratios (SS:LS = 50:50 and RCA:LS = 50:50). In addition, the cement-NRL stabilized 70SS:30LS samples exhibited higher ITS values than that of cement-NRL stabilized 70RCA:30LS samples at the optimum r/c ratios. This is because SS had higher resistance to abrasion and angularness than RCA.

It was evident that the r/c ratio had a direct influence on both UCS and ITS of the studied blends. The maximum UCS and ITS values of 7-day and 28-day samples were obtained at the optimum r/c ratios of 3 % and 5 % respectively for cement-NRL stabilized 70SS:30LS and 50SS:50LS samples and cement-NRL stabilized 70RCA:30LS and 50RCA:50 samples. Figs. 7 and 8 show the relationships between the 7-day UCS versus 28-day UCS and 7-day ITS versus 28-day ITS of the studied blends with and without NRL, respectively. The rate of UCS and ITS development over time was found to be the same for different replacement materials and replacement ratios. In general, the UCS and ITS development of cement stabilized materials is primarily governed by cement hydration products. This implies that the addition of NRL and replacement materials did not alter the rate of cementation bond strength over time of cement stabilized materials. Since both UCS and ITS development of cement stabilized materials are primarily dependent upon the cementation bond strength, it is on sound engineering principles and practices to establish the relationship between ITS and UCS for cement-NRL stabilized SS:LS and RCA:LS as shown in Fig. 9. The ITS is commonly used to estimate the tensile or flexural cracking resistance of cement stabilized aggregate but the test is more complicated and time-consuming than the UCS test. The establishment of the correlation between UCS and ITS is therefore cost-effective and time-savings for geotechnical and pavement engineering design [59–62]. It is noted that the linear regression analysis exhibited the p-value < 0.000, which ensuring more than 95 % confidence level of the developed models in Figs. 7, 8 and 9.

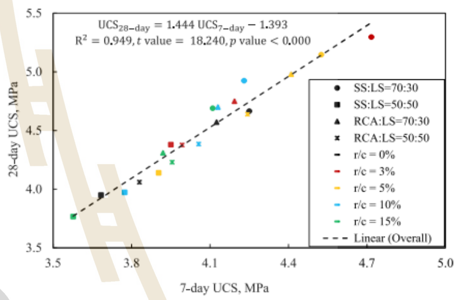


Fig. 7. Relationship between 7-day and 28-day UCS of cement-NRL stabilized SS:LS and RCA:LS samples at different r/c ratios.

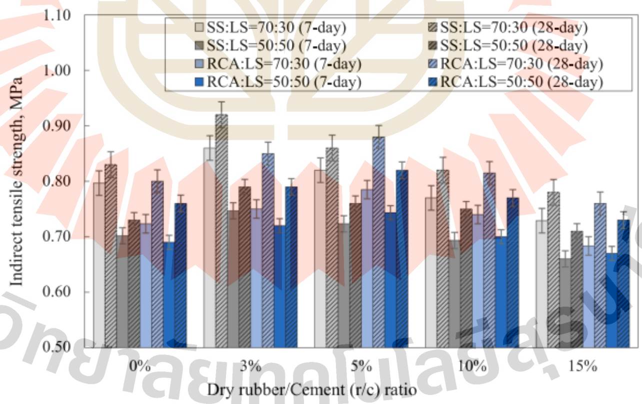


Fig. 6. Indirect tensile strength of cement- and cement-NRL stabilized SS:LS and RCA:LS samples at various r/c ratios.

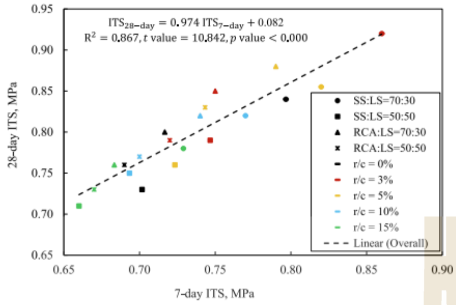


Fig. 8. Relationship between 7-day and 28-day ITS of cement-NRL stabilized SS:LS and RCA:LS samples at different r/c ratios.

3.4. Microstructural analysis

3.4.1. Scanning electron microscopic analysis

SEM analysis was conducted to inspect the change in microstructure of cement stabilized and cement-NRL stabilized samples, which cannot be observed by naked eyes. In this research, the cementitious products: calcium hydroxide (CH), calcium silicate hydrate (C—S—H), ettringite, NRL film, and pores are the important components to be examined. The change in soil structure associated with the interparticle bond strength, porosity and interconnected films is shown by the growth of cement hydration reaction and NRL film in pore spaces. Fig. 10**(a-f)** illustrates the SEM images of cement stabilized and cement-NRL stabilized SS:LS and RCA:LS samples at an age of 28 days.

Fig. 10**a and 10b** demonstrate SEM images of cement stabilized 70SS:30LS and 70RCA:30LS samples; the cementitious products were clearly detected in the pore space. The presence of cement hydration products resulted in the reduction of the void ratio and the increase of interparticle bond strength, which led to the development of mechanical strength [18,63]. The SEM images of cement-NRL stabilized 70SS:30LS at optimum r/c ratio of 3 % and cement-NRL stabilized 70RCA:30LS at optimum r/c ratio of 5 % are shown in Fig. 10**c and 10d**, respectively. The NRL films coexisted with the cementitious products were clearly detected in the pore space of the soil structures. In other words, the NRL film infiltrated the pore space that has not been filled by the cementitious products and resulted in the decrease in porosity. Consequently, UCS and ITS of the hardened cement-NRL stabilized blends were improved [14]. However, a thicker NRL film network was generated from the excessive NRL volume, which was detected by SEM images of cement-NRL stabilized 70SS:30LS and 70RCA:30LS at r/c ratio of 15 % (Fig. 10**e and 10f**, respectively). The thicker films covered the cement grains and aggregates and acted as a barrier of water absorption, which might cause insufficient water for cement hydration. In other words, it retarded the hydration process and led to low UCS and ITS development of cement-NRL stabilized blends.

3.4.2. X-ray diffraction analysis

The mineralogical modifications in soil fabric can be analyzed by XRD analysis. The XRD patterns illustrate the amount of crystalline phase formation that represents the original aggregates and the cement hydrates. The X-axis in the pattern is in 2θ degree and the Y-axis is the intensity of the diffracted beam. Fig. 11 shows XRD patterns of cement stabilized and cement-NRL stabilized 70SS:30LS and 70RCA:30LS samples at the optimum r/c ratio and on dry and wet sides of optimum. The XRD patterns illustrate main phases including quartz (SiO_2), calcite ($CaCO_3$), and calcium silicate hydrate (CaO-SiO_2-H_2O).

The mineralogy (XRD pattern) of cement stabilized 70SS:30LS and 70RCA:30LS was altered by the addition of NRL additive (compared Fig. 11**a-b** to Fig. 11**c-f**). It can be seen that the peak intensity of quartz and calcite were changed. They are the main compositions attribute to the carbonation of cement hydrates and result in mechanical strength development [16,17,64]. It is evident from the XRD analysis that the cement hydration of both cement-NRL stabilized SS:LS and RCA:LS decreased with the increased rubber content. Similarly, the effect of latex polymer on the degree of cement hydration of cement-latex mortar and soil stabilization was found to be reduced with the increased solid rubber content [65].

In addition, the variation of quartz (Si) and calcite (Ca), which are the dominant minerals governing the hydration of cement stabilization, was also discovered in this research. Kunther, Ferreiro and Skibsted [66] investigated the influence of the Ca/Si ratio on the UCS of cementitious products binders and indicated that the higher strength of cemented materials can be obtained at lower Ca/Si ratio. In this study, the Ca/Si ratio of cement stabilized SS:LS and RCA:LS samples was changed with

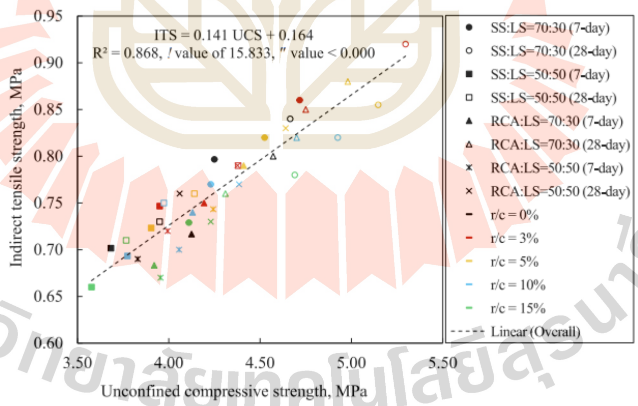
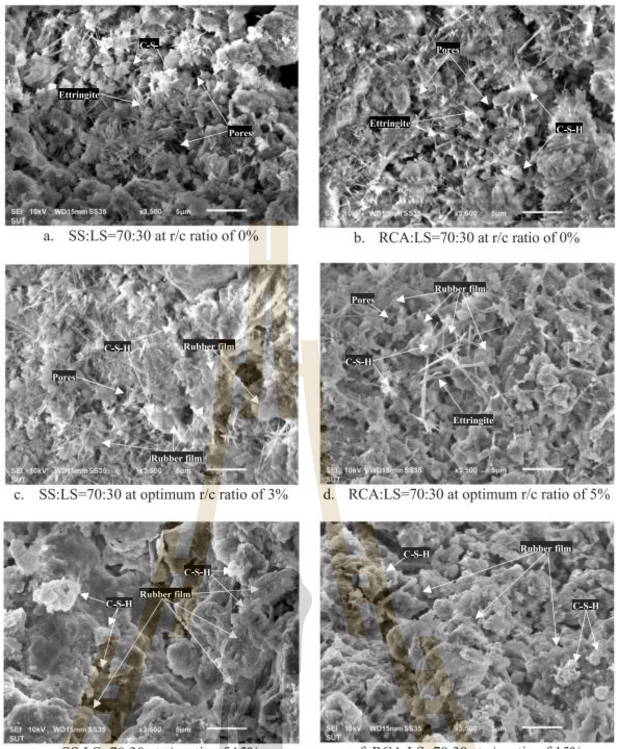


Fig. 9. Relationship between ITS and UCS of cement-NRL stabilized SS:LS and RCA:LS samples.



a. SS:LS=70:30 at r/c ratio of 0%
b. RCA:LS=70:30 at r/c ratio of 0%
c. SS:LS=70:30 at optimum r/c ratio of 3%
d. RCA:LS=70:30 at optimum r/c ratio of 5%
e. SS:LS=70:30 at r/c ratio of 15%
f. RCA:LS=70:30 at r/c ratio of 15%

Fig. 10. Scanning electron microscope images of cement stabilized and cement-NRL stabilized SS:LS and RCA:LS samples at ages of 28 days.

the addition of NRL additive and was influenced by r/c ratio. It was clearly evident that the highest compressive and tensile strength values of cement-NRL stabilized SS:LS and RCA:LS at optimum r/c ratios were obtained at the lowest Ca/Si ratios as shown in Fig. 12.

SEM and XRD analyses confirmed that the UCS and ITS development of cement-NRL stabilized SS:LS and RCA:LS samples was influenced by the r/c ratio in which the samples at the excess NRL prevented the hydration process and hence fewer hydration products were detected, leading to the reduction of UCS and ITS. However, at the optimum r/c ratio, SEM images demonstrated that the cement-NRL mixture was improved by the formation of latex network (films) and membranes, resulted in the UCS and ITS development [67].

The results of this research illustrated the role of NRL in mechanical strength enhancement of cement-stabilized recycled aggregates and soil mixtures. With an appropriate amount of NRL, the interparticle bond strength and microstructure of samples are enhanced and therefore the mechanical strength is improved. This confirms that NRL can be used as a natural non-traditional additive in the sustainable stabilization of pavement base materials.

4. Conclusions

This study investigated the influence of NRL additive on UCS and ITS development of cement-stabilized lateritic soil (LS) with recycled aggregates such as SS and RCA. The SS and RCA replacement ratios were SS:LS = 70:30, and 50:50, and RCA:LS = 70:30 and 50:50. The cement content of 5 % by weight of aggregate and dry NRL to cement (r/c) of 0 %, 3 %, 5 %, 10 %, 15 % were investigated. The SEM and XRD analyses were also conducted to ascertain the effect of the influence factors on their UCS and ITS development. The following are the significant conclusions obtained from this research:

1. The r/c ratios had the influence on the compactability, UCS, and ITS of cement-NRL stabilized SS:LS and RCA:LS blends. The optimum r/c ratios provided the lubrication of aggregate particles and led to the denser structure of the blends. The cement hydration reaction and film formation of NRL empower the interparticle bond strength and resulted in development in both UCS and ITS. The highest MDD, UCS, and ITS of cement-NRL stabilized SS:LS and RCA:LS blends were found at optimum r/c ratios. The optimum r/c ratios were found to be 3 % for cement-NRL stabilized 70SS:30LS and 50SS:50LS samples, and 5 % for cement-NRL stabilized 70RCA:30LS and 50RCA:50LS samples.
2. The UCS and ITS values of cement-NRL stabilized SS:LS and RCA:LS samples depend upon the r/c ratio and curing time. The UCS and ITS development patterns of cement-NRL stabilized SS:LS and RCA:LS were found to be similar; UCS and ITS increased with increasing the r/c ratio until the maximum value at the optimum r/c ratio and then

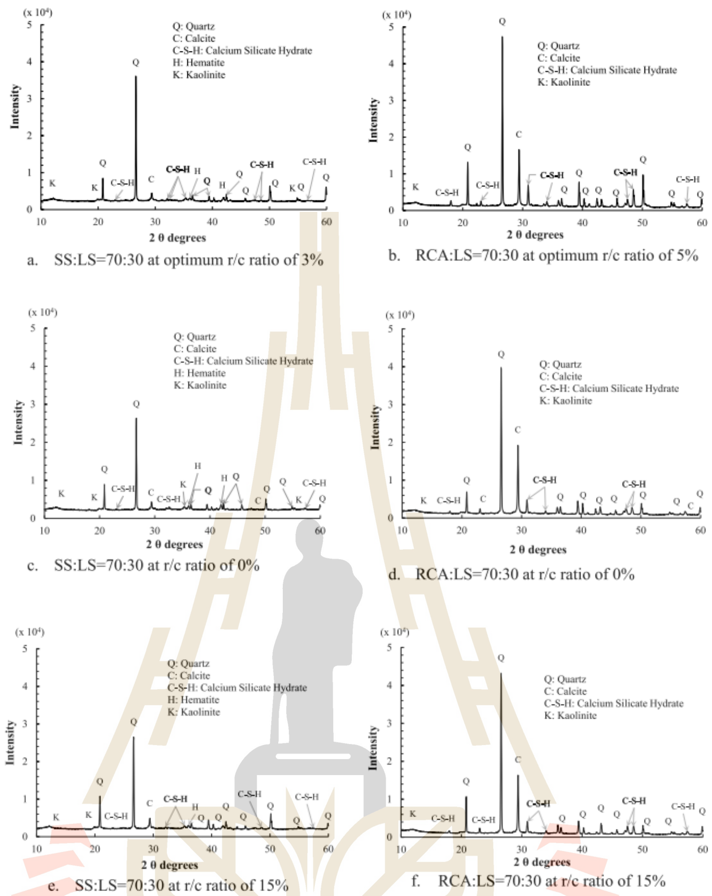


Fig. 11. X-ray diffraction patterns of cement stabilized and cement-NRL stabilized SS:LS and RCA:LS samples at ages of 28 days.

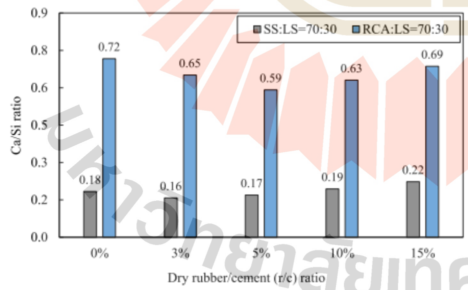


Fig. 12. The variation of Ca/Si ratios of cement stabilized and cement-NRL stabilized SS:LS and RCA:LS at different dry rubber/cement ratios.

declined with further increase in r/c ratio. At the optimum r/c ratios, the UCS and ITS values of both cement-NRL stabilized SS:LS and RCA:LS samples were higher than those of the cement-stabilized SS: LS and RCA:LS (r/c ratio = 0 %) samples. This confirms that the addition of NRL can enhance the cement stabilized SS/RCA and soil blends. In addition, at a high replacement ratio of 70 %, the UCS and ITS of cement-NRL stabilized SS:LS blends were higher than that of cement-NRL stabilized RCA:LS blends at the same optimum r/c ratio. This is because SS had higher resistance to abrasion and angularness than RCA.

3. The UCS and ITS development of cement-NRL stabilized SS:LS and RCA:LS blends were found to be reliant on the r/c ratio. Hence, the direct relationship between UCS and ITS of cement-NRL stabilized SS:LS and RCA:LS samples at various r/c ratios with high reliability and accuracy could be established. This information is useful for predicting the mechanical strength for pavement engineering design.

4. SEM and XRD analyses confirmed that the hydration products of cement-NRL stabilized SS:LS and RCA:LS samples decreased with the increased NRL content. The excess NRL created a thicker NRL film network which covered the aggregate-cement matrix and retarded the hydration process. This led to the weaker structures and the drop of UCS and ITS. However, at the optimum r/c ratios, the coexistence between hydration products and the NRL films increased the inter-particle bond strength and filled up the pore spaces. As a result, the void ratio of the cement-NRL stabilized blends was reduced, and therefore the UCS and ITS were improved.

CRediT authorship contribution statement

Ngoc Quynh Tran: Formal analysis, Writing – original draft. **Menglim Hoy:** Project administration, Supervision, Conceptualization, Funding acquisition, Writing – original draft, Methodology. **Apichat Suddeepong:** Methodology, Conceptualization. **Suksun Horpibulsuk:** Supervision, Funding acquisition, Methodology, Writing – review & editing. **Karn Kantathum:** Methodology. **Arul Arulrajah:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This work was financially supported by the National Science and Technology Development Agency under the Chair Professor program Grant No. P-19-52303, Suranaree University of Technology and Thailand Science Research and Innovation (TSRI). This research project was also funded by National Research Council of Thailand (NRCT) under Young Researcher Genius Program Grant No. N42A650210.

Appendix I. Abbreviation

CB	Crushed Brick
CBR	California Bearing Ratio
CCR	Calcium Carbide Residue
CH	Calcium hydroxide
C-S-H	Calcium silicate hydrate
DOH	Department of Highways
FA	Fly Ash
ITS	Indirect Tensile Strength
LS	Lateritic Soil
MDD	Maximum dry density
NRL	Natural Rubber Latex
OWC	Optimum water content
PET	Plastic Polyethylene Terephthalate
RAP	Recycled Asphalt Pavement
RCA	Recycled Concrete Aggregate
SDS	Sodium dodecyl sulphate
SEM	Scanning electron microscopy
SS	Steel Slag
UCS	Unconfined Compressive Strength
XRD	X-ray diffractometer
ZMBT	Zinc 2-mercaptobenzothiazole

References

[1] K.J. Osinubi, C.M. Nwaiwu, Design of Compacted Lateritic Soil Liners and Covers, J. Geotech. Geoenviron. Eng. 132 (2) (2006) 203–213.
[2] P. Maichin, P. Jitsangiam, T. Nongnuang, K. Boonserm, K. Nusit, S. Pra-Ai, T. Binaree, C. Aryupong, Stabilized High Clay Content Lateritic Soil Using Cement-FGD Gypsum Mixtures for Road Subbase Applications, Materials 14 (8) (2021) 1858.
[3] J. Camapum de Carvalho, L.R. de Rezende, F.B.d.F. Cardoso, L.C.d.F.L. Lucena, R. C. Guimarães, Y.G. Valencia, Tropical soils for highway construction: Peculiarities and considerations, Transp. Geotech. 5 (2015) 3–19.
[4] D.G. Toll, B. Caicedo, Special issue on lateritic and tropical geomaterials in construction of transportation infrastructures, Transp. Geotech. 5 (2015) 1–2.
[5] F.H.C. Pessoa, Análises dos solos de Urucu para fins de uso rodoviário, Distrito Federal, 2004.
[6] J.C.B. Benatti, M.G. Miguel, A proposal of structural models for colluvial and lateritic soil profile from southwestern Brazil on the basis of their collapsible behavior, Eng. Geol. 153 (2013) 1–11.
[7] I.F. Otálvaro, M.P.C. Neto, B. Caicedo, Compressibility and microstructure of compacted laterites, Transp. Geotech. 5 (2015) 20–34.
[8] K.C. Onyelowe, Nanosized palm bunch ash (NPBA) stabilisation of lateritic soil for construction purposes, Int. J. Geotech. Eng. 13 (1) (2019) 83–91.
[9] S. Horpibulsuk, W. Katkan, W. Sirilerdwattana, R. Rachan, Strength Development in Cement Stabilized Low Plasticity and Coarse Grained Soils: Laboratory and Field Study, Soils Found. 46 (3) (2006) 351–366.
[10] F. Sariosseiri, B. Muhunthan, Effect of cement treatment on geotechnical properties of some Washington State soils, Eng. Geol. 104 (1) (2009) 119–125.
[11] A.W. Otunyo, C.C. Chukuigwe, Investigation of the impact of palm bunch ash on the stabilization of poor lateritic soil, Nigerian Journal of Technology 37 (3) (2018) 600.
[12] B. Tugume, I. Owani, S. Jjuuko, D. Kalumba, Performance of Lateritic Soils Stabilized with Both Crushed Rock Aggregates and Carbon Black as a Pavement Base Layer, Springer, The International Congress on Environmental Geotechnics, 2018, pp. 382–388.
[13] M. Joel, I.O. Agbede, Mechanical-Cement Stabilization of Laterite for Use as Flexible Pavement Material, J. Mater. Civ. Eng. 23 (2) (2011) 146–152.
[14] A. Buritatun, T. Takaikaew, S. Horpibulsuk, A. Udomchai, M. Hoy, N. Vichitcholchai, A. Arulrajah, Mechanical strength improvement of cement-stabilized soil using natural rubber latex for pavement base applications, J. Mater. Civ. Eng. 32 (12) (2020) 04020372.
[15] I. Phummiphan, S. Horpibulsuk, P. Sukmak, A. Chinkulkijniwat, A. Arulrajah, S.-L. Shen, Stabilisation of marginal lateritic soil using high calcium fly ash-based geopolymer, Road Materials and Pavement Design 17 (4) (2016) 877–891.
[16] K. Abdulhussein Saeed, S. Abdul Muttaleb Hashim, Micro-structural characterization of cement stabilized tropical Laterite clay soil contaminated by heavy metals, Journal of Engineering and Sustainable Development (JEASD) 22 (02) (2018) 134–145.
[17] M. Dafalla, E. Mutaz, Study of the mineralogical changes of clay due to cement and lime addition using X ray diffraction technique, Res. J. Appl. Sci. Eng. Technol 4 (19) (2012) 3746–3754.

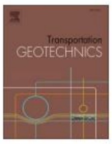
[18] S. Horpibulsuk, R. Rachan, A. Chinkulkijniwat, Y. Raksachon, A. Suddeepong, Analysis of strength development in cement-stabilized silty clay from microstructural considerations, Constr. Build. Mater. 24 (10) (2010) 2011–2021.
[19] E. Mengue, H. Mroueh, L. Lancelot, R.M. Eko, Mechanical Improvement of a Fine-Grained Lateritic Soil Treated with Cement for Use in Road Construction, J. Mater. Civ. Eng. 29 (11) (2017) 04017206.
[20] N.A. Wahab, M.J. Roshan, A.S.A. Rashid, M.A. Hezmi, S.N. Jusoh, N.D. Nik Norsyahariati, S. Tamassoki, Strength and Durability of Cement-Treated Lateritic Soil, Sustainability 13 (11) (2021) 6430.
[21] N.C. Consoli, D. Párraga Morales, R.B. Saldanha, A new approach for stabilization of lateritic soil with Portland cement and sand: strength and durability, Acta Geotech. 16 (5) (2021) 1473–1486.
[22] A. Arulrajah, S. Perera, Y.C. Wong, S. Horpibulsuk, F. Maghool, Stiffness and flexural strength evaluation of cement stabilized PET blends with demolition wastes, Constr. Build. Mater. 239 (2020), 117819.
[23] M. Koohmishi, M. Palassi, Mechanical Properties of Clayey Soil Reinforced with PET Considering the Influence of Lime-Stabilization, Transportation Geotechnics (2022) 100726.
[24] F. Maghool, A. Arulrajah, B. Ghorbani, S. Horpibulsuk, Strength and permanent deformation properties of demolition wastes, glass, and plastics stabilized with foamed bitumen for pavement bases, Constr. Build. Mater. 320 (2022), 126108.
[25] A. Arulrajah, A. Mohammadinia, I. Phummiphan, S. Horpibulsuk, W. Samingthong, Stabilization of Recycled Demolition Aggregates by Geopolymers comprising Calcium Carbide Residue, Fly Ash and Slag precursors, Construction and Building Materials 114 (2016) 864–873.
[26] J. Donrak, S. Horpibulsuk, A. Arulrajah, H.-L. Kou, A. Chinkulkijniwat, M. Hoy, Wetting-drying cycles durability of cement stabilised marginal lateritic soil/melamine debris blends for pavement applications, Road Materials and Pavement Design 21 (2) (2020) 500–518.
[27] D. Jeerapan, H. Menglim, H. Suksun, A. Arul, M. Mehdi, R.a.s. a,, Environmental assessment of cement-stabilised lateritic soil/melamine debris for Thailand's pavement, Environmental Geotechnics (2019) 1–7.
[28] M. Hoy, S. Horpibulsuk, R. Rachan, A. Chinkulkijniwat, A. Arulrajah, Recycled asphalt pavement – fly ash geopolymers as a sustainable pavement base material: Strength and toxic leaching investigations, Sci. Total Environ. 573 (2016) 19–26.
[29] I. Barišić, S. Dimter, T. Rukavina, Strength properties of steel slag stabilized mixes, Compos. B Eng. 58 (2014) 386–391.
[30] P. Sudla, S. Horpibulsuk, A. Chinkulkijniwat, A. Arulrajah, M.D. Liu, M. Hoy, Marginal lateritic soil/crushed slag blends as an engineering fill material, Soils Found. 58 (3) (2018) 786–795.
[31] A. Ebrahim Abu El-Maaty Behiry,, Utilization of cement treated recycled concrete aggregates as base or subbase layer in Egypt, Ain Shams Eng. J. 4 (4) (2013) 661–673.
[32] M. Maslehuddin, A.M. Sharif, M. Shameem, M. Ibrahim, M.S. Barry, Comparison of properties of steel slag and crushed limestone aggregate concretes, Constr. Build. Mater. 17 (2) (2003) 105–112.
[33] H. Qasrawi, The use of steel slag aggregate to enhance the mechanical properties of recycled aggregate concrete and retain the environment, Constr. Build. Mater. 54 (2014) 298–304.
[34] P. Sudla, J. Donrak, M. Hoy, S. Horpibulsuk, A. Arulrajah, A.S.A. Rashid, R. Nazir, W. Samingthong, Laboratory Investigation of Cement-Stabilized Marginal Lateritic Soil by Crushed Slag-Fly Ash Replacement for Pavement Applications, J. Mater. Civ. Eng. 32 (2) (2020) 04019353.
[35] A.A.S. Correia, P.J. Venda Oliveira, D.G. Custódio, Effect of polypropylene fibres on the compressive and tensile strength of a soft soil, artificially stabilised with binders, Geotext. Geomembr. 43 (2) (2015) 97–106.
[36] M.J. Khattak, M. Alrashidi, Durability and mechanistic characteristics of fiber reinforced soil–cement mixtures, Int. J. Pavement Eng. 7 (1) (2006) 53–62.
[37] T. Yaowarat, A. Suddeepong, M. Hoy, S. Horpibulsuk, T. Takaikaew, N. Vichitcholchai, A. Arulrajah, A. Chinkulkijniwat, Improvement of flexural strength of concrete pavements using natural rubber latex, Constr. Build. Mater. 282 (2021), 122704.
[38] P. Jamsawang, P. Voottipruex, S. Horpibulsuk, Flexural Strength Characteristics of Compacted Cement-Polypropylene Fiber Sand, J. Mater. Civ. Eng. 27 (9) (2015) 04014243.
[39] A.R. Estabragh, I. Beytolahpour, A.A. Javadi, Effect of Resin on the Strength of Soil-Cement Mixture, J. Mater. Civ. Eng. 23 (7) (2011) 969–976.
[40] A. Jose, A.K. Kasthurba, Laterite soil-cement blocks modified using natural rubber latex: Assessment of its properties and performance, Constr. Build. Mater. 273 (2021), 121991.
[41] J.S. Tingle, R.L. Santoni, Stabilization of Clay Soils with Nontraditional Additives, Transp. Res. Rec. 1819 (1) (2003) 72–84.
[42] M.S. Baghini, A. Ismail, S.S. Naseralavi, A.A. Firoozi, Performance evaluation of road base stabilized with styrene–butadiene copolymer latex and Portland cement, Int. J. Pavement Res. Technol. 9 (4) (2016) 321–336.
[43] T. Yaowarat, W. Sudsaynate, S. Horpibulsuk, A. Chinkulkijniwat, A. Arulrajah, J. Horpibulsuk, Mechanical Properties of Fly Ash-Asphalt Emulsion Geopolymer Stabilized Crushed Rock for Sustainable Pavement Base, J. Mater. Civ. Eng. 33 (9) (2021) 04021220.
[44] T. Yaowarat, S. Horpibulsuk, A. Arulrajah, F. Maghool, M. Mirzababaei, A.S. A. Rashid, A. Chinkulkijniwat, Cement stabilisation of recycled concrete aggregate modified with polyvinyl alcohol, Int. J. Pavement Eng. 23 (2) (2022) 349–357.
[45] M.L. Vo, J. Plank, Evaluation of natural rubber latex as film forming additive in cementitious mortar, Constr. Build. Mater. 169 (2018) 93–99.
[46] B. Muhammad, M. Ismail, M.A.R. Bhutta, Z. Abdul-Majid, Influence of non-hydrocarbon substances on the compressive strength of natural rubber latex-modified concrete, Constr. Build. Mater. 27 (1) (2012) 241–246.
[47] G. Sukmak, P. Sukmak, S. Horpibulsuk, T. Yaowarat, K. Kunchariyakun, O. Patarapaiboolchai, A. Arulrajah, Physical and mechanical properties of natural rubber modified cement paste, Constr. Build. Mater. 244 (2020), 118319.
[48] DH-S203/2556, Standard for highway construction (Cement Modified Crushed Rock Base), Department of Highways, Bangkok, Thailand 2013.
[49] DH-S204/2556, Standard for highway construction (Soil Cement Base), Department of Highways, Bangkok, Thailand 2013.
[50] DH-S201/2544, Standard for highway construction (Crush Rock Soil Aggregate Type), Department of Highways, Bangkok, Thailand., 2001.
[51] DH-S210/2547, Standard for highway construction (Crushed Slag), Department of Highways, Bangkok, Thailand., 2004.
[52] ASTM-D1241, Standard Specification for Materials for Soil-Aggregate Subbase, Base, and Surface Courses, ASTM International, West Conshohocken, PA, 2016.
[53] AASHTO-M-147, Standard Specification for Materials for Aggregate and Soil–Aggregate Subbase, Base, and Surface Courses, American Association of State Highway and Transportation Officials (AASHTO), 2017.
[54] I. Phummiphan, S. Horpibulsuk, R. Rachan, A. Arulrajah, S.-L. Shen, P. Chindaprasirt, High calcium fly ash geopolymer stabilized lateritic soil and granulated blast furnace slag blends as a pavement base material, J. Hazard. Mater. 341 (2018) 257–267.
[55] ASTM-D1557, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2,700 kN-m/m3)). West Conshohocken, (2012).
[56] ASTM-D1633, Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders. West Conshohocken, 2017.
[57] ASTM-D6931, Standard Test Method for Indirect Tensile (IDT) Strength of Asphalt Mixtures. West Conshohocken, 2017.
[58] M.S. Baghini, A. Ismail, M.R. Bin Karim, Evaluation of cement-treated mixtures with slow setting bitumen emulsion as base course material for road pavements, Constr. Build. Mater. 94 (2015) 323–336.
[59] F. Din, M. Rafiq, Correlation between compressive strength and tensile strength/index strength of some rocks of North-West Frontier Province (limestone and granite), Geol. Bull. Univ. Peshawar 30 (1997) 183.
[60] R. Nazir, E. Momeni, D.J. Armaghani, M.M. Amin, Correlation between unconfined compressive strength and indirect tensile strength of limestone rock samples, Electron J Geotech Eng 18 (1) (2013) 1737–1746.
[61] S. Wang, F. Chen, Q. Xue, P. Zhang, Splitting Tensile Strength of Cement Soil Reinforced with Basalt Fibers, Materials 13 (14) (2020) 3110.
[62] C. Chhorn, S.J. Hong, S.W. Lee, Relationship between compressive and tensile strengths of roller-compacted concrete, Journal of Traffic and Transportation Engineering (English Edition) 5 (3) (2018) 215–223.
[63] T. Imtiaz, A. Ahmed, M.S. Hossain, M. Faysal, Microstructure Analysis and Strength Characterization of Recycled Base and Sub-Base Materials Using Scanning Electron Microscope, Infrastructures 5 (9) (2020) 70.
[64] P. Sukmak, G. Sukmak, S. Horpibulsuk, M. Setkit, S. Kassawat, A. Arulrajah, Palm oil fuel ash-soft soil geopolymer for subgrade applications: strength and microstructural evaluation, Road Materials and Pavement Design 20 (1) (2019) 110–131.
[65] A.M. Diab, H.E. Elyamany, A.H. Ali, Experimental investigation of the effect of latex solid/water ratio on latex modified co-matrix mechanical properties, Alexandria Engineering Journal 52 (1) (2013) 83–98.
[66] W. Kunther, S. Ferreiro, J. Skibsted, Influence of the Ca/Si ratio on the compressive strength of cementitious calcium–silicate-hydrate binders, J. Mater. Chem. A 5 (33) (2017) 17401–17412.
[67] Y. Ohama, Handbook of polymer-modified concrete and mortars: properties and process technology, William Andrew1995.

Transportation Geotechnics 40 (2023) 100959

Contents lists available at ScienceDirect

Transportation Geotechnics

journal homepage: www.elsevier.com/locate/trgeo



Improved fatigue properties of cement-stabilized recycled materials – Lateritic soil using natural rubber latex for sustainable pavement applications

Menglim Hoy [a,*], Ngoc Quynh Tran [b], Apichat Suddeepong [c], Suksun Horpibulsuk [a,d,1], Manlika Mobkrathok [e], Avirut Chinkulkijniwat [b,*], Arul Arulrajah [f]

[a] School of Civil Engineering, Institute of Engineering, Center of Excellence in Innovation for Sustainable Infrastructure Development, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
[b] School of Civil Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
[c] School of Civil and Infrastructure Engineering, Institute of Engineering, Center of Excellence in Innovation for Sustainable Infrastructure Development, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
[d] Academy of Science, The Royal Society of Thailand, Bangkok 10300, Thailand
[e] Center of Excellence in Innovation for Sustainable Infrastructure Development, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
[f] Department of Civil and Construction Engineering, Swinburne University of Technology, Melbourne, Australia

ARTICLE INFO

Keywords:
Natural rubber latex
Mechanistic-empirical approach
Resilient modulus
Fatigue life
Permanent deformation
Soil-cement
Ground improvement
Pavement geotechnics
Waste materials

ABSTRACT

This research project investigates the role of a new recycled pavement material and natural rubber latex (NRL), in improving the resilient and fatigue performances of cement-stabilized recycled materials and lateritic soil (LS) blends under traffic loads. Two types of recycled materials, being steel slag (SS) and recycled concrete aggregate (RCA) and 5% cement content by weight were studied in this research. The dry rubber content in NRL to cement (r/c) ratios of 0%, 3%, 5%, 10%, and 15% were designed as the influence factor. The results indicated that mechanical strength properties namely unconfined compressive strength (UCS) and indirect tensile test (ITS), as well as fatigue properties namely indirect tensile resilient modulus (IT M_r) and indirect tensile fatigue (ITF) were enhanced with the NRL additive. Beyond the optimum r/c ratio, the excessive amount of NRL generated thick NRL films and retarded the cement hydration products, resulting in low strength and performance improvement. The r/c ratios of 3% and 5% were found to be the optimum r/c ratios for cement-NRL stabilized SS:LS and RCA:LS blends, respectively. The brittleness and permanent deformation of cement-stabilized SS/RCA:LS blends were significantly improved by the NRL additive. The superior mechanical and physical properties of SS and RCA were also attributed to the enhancement of fatigue characteristics of the cement-NRL stabilized blends. Finally, the mechanistic and fatigue models of cement- and cement-NRL stabilized soil with recycled material replacements were proposed, which are important for pavement designers and engineers when using a mechanistic-empirical pavement design approach.

Introduction

The base course is an essential component of the pavement structure that determines the quality and lifespan of the roads. In recent years, the significant increase in traffic load and volume has led to the shorter lifespan of the roads, which motivates researchers to conduct research concerning novel pavement improvement techniques. Cement, fly ash, lime, and slag are cementing binders that produce cementitious products through the hydration process to transfer the unfavored material into a strong bound pavement material. The cementitious products improve the strength of the structural base course by distributing the load over the larger area, hence the base layer's required thickness can be reduced.

Chemical stabilization of pavement materials is often considered for a cost-effective pavement design in Southeast Asia countries. Moffat

* Corresponding authors.
E-mail addresses: menglim@g.sut.ac.th (M. Hoy), ttnquynh@hueuni.edu.vn (N.Q. Tran), suddeepong@g.sut.ac.th (A. Suddeepong), suksun@g.sut.ac.th (S. Horpibulsuk), minymixky@gmail.com (M. Mobkrathok), avirut@sut.ac.th (A. Chinkulkijniwat), aarulrajah@swin.edu.au (A. Arulrajah).
[1] School of Civil Engineering, Suranaree University of Technology, 111 University Avenue, Muang District, Nakhon Ratchasima 30000, Thailand.

https://doi.org/10.1016/j.trgeo.2023.100959
Received 26 December 2022; Received in revised form 10 February 2023; Accepted 11 February 2023
Available online 16 February 2023

et al. [45] studied the performance comparison of bound and unbound granular pavement materials. It was reported that though the cost of stabilized materials might increase 2–3 times while its deformation resistance could be 6–10 times superior to the unbound layer. Portland cement is the most common binder used in chemical stabilization because of its convenience to implement in the field and its rapid improvement of mechanical properties [31–32]. Sobhan and Das [54] indicated that cement hydration products enhance the chemical bonding of cement-stabilized materials and result in strength development. Arora and Aydilek [4] and [17–18] reported that the unconfined compressive strength (UCS) and indirect tensile resilient modulus (IT $M_r$values of cement-stabilized soil materials could be increased with the increase of cement content. The pavement structure's stiffness affects the load distribution; the stiff cement-stabilized base can distribute traffic loads over a larger area, decreasing subgrade stresses and preserving the original grade for many years without expensive resurfacing or repairs [20].

Cement stabilization has been effectively applied to improve the properties of several materials, such as soils, granular materials, and recycled aggregates. Cement stabilization can increase cohesion of cohesionless soil, thus enhancing its strength and durability. Furthermore, cement stabilization can be used to improve expansive clayey soil's mechanical properties and mitigate linear shrinkage and water absorption [28]. Horpibulsuk et al. [31–32] also reported that the proper cement content could improve mechanical properties of silty clay, lateritic soil, and crushed rock.

To reduce the environmental burden from demolition and industrial wastes and save the construction cost, recycled materials such as recycled concrete aggregate (RCA) and steel slag (SS) have been widely utilized as aggregates in cement stabilization for sustainable pavement applications [2,5,8,10,19,33,42,53]. However, a rapid loss of moisture at early stage of cement stabilization leads to shrinkage and cracking of the pavement base course (Buritatum et al., 2022b). Hence, instead of cement usage as a single additive, synthetic polymers such as polyvinyl alcohol and asphalt emulsion have been used as a compound additive to enhance the microstructural and tensile/flexural properties of cement-stabilized base materials [9,24,41,58,65–66].

One of the natural polymers that have been commonly used in recent research is natural rubber latex (NRL), which has demonstrated effectiveness in enhancing the strength and durability of cement stabilization because of its high elastic and tensile properties [17–18,37,59]. Tran et al. [59] investigated the UCS development of cement-NRL stabilized lateritic soil with RCA and SS replacement and illustrated that the UCS meets the minimum strength requirement designated by the Department of Highways (DOH), Thailand as a base material. However, in the field condition, repetitive stress by the traffic loads is generated instead of unconfined compressive stress; the UCS alone may not apply to the actual situations [40,57]. The cyclic traffic loads typically cause vertical compressive and horizontal tensile stresses in the pavement base layer [38]. The cumulative irreversible deformation caused over time by repeated tensile stress eventually leads to fatigue-cracking failure [54]. Several studies demonstrated the importance of fatigue properties of cement-stabilized base materials for pavement thickness design; the selected base material must withstand the critical repeated loads and prevent excessive permanent deformation during the service lifetime [12,14,35,43,51,55,63,64]. The parameters that affect the tensile properties of cement stabilized materials were investigated previously [21,27]. Festugato et al. [27] found that the resilient modulus and fatigue life were directly proportional to the cement content and inversely proportional to the porosity of cement-stabilized sand.

The tensile strength and stiffness modulus of the materials are essential for pavement design following the mechanistic-empirical pavement design guideline. The pavement thickness design is based on the fatigue-cracking failure criteria, which is obtained from a relationship between tensile strain and fatigue life of the cement-stabilized material. The tensile property of cement-stabilized materials can be measured by direct or indirect tensile, and flexural beam tests. The test under cyclic flexural stress is considered as the most important condition for evaluating the fatigue response [52]. However, several researchers have recommended indirect tensile testing instead as a cost and time effective method [16,50].

Therefore, to investigate the effective utilization of natural rubber latex in cement- stabilized lateritic soil with RCA and SS as pavement base materials, the indirect tensile resilient modulus and indirect tensile fatigue life under cyclic load conditions were performed. The relationship between the UCS, ITS, IT-M_r, permanent deformation, and fatigue life of those cement-stabilized lateritic soil with different recycled aggregate replacements was established, which are viral parameters for structural pavement design in the mechanistic empirical approach.

Materials and Sample Preparation

Materials

Aggregates of this research included lateritic soil (LS), steel slag (SS), and recycled concrete aggregate (RCA). LS and SS were collected from Nakhon Ratchasima province and Siam Steel Mill Services Co., ltd., Chonburi province, Thailand, respectively while RCA was obtained from crushed concrete structures in Nakhon Ratchasima province. Fig. 1 shows the grain size distribution of LS, SS, and RCA and compares it with the base gradation limits designed by the Department of Highways (DOH), Thailand, similar to AASHTO M 147. The liquid limit and plastic limit of LS were 21 % and 8 %, respectively, while the SS and RCA were non-plastic material. The LS, RCA, and SS had a specific gravity of 2.78, 2.57, and 3.64, respectively. The maximum dry unit weight of LS, RCA, and SS was 21.30 kN/m^3, 19.60 kN/m^3, and 27.00 kN/m^3, respectively, at the optimum water content of 8.1, 12.0, and 6.05 %. LS, RCA, and SS had a Los Angeles abrasion value of 34, 31, and 17.2 %, respectively, and were lower than the maximum allowance of 40 % specified by DOH, Thailand. The aggregate material required a minimum California bearing ratio (CBR) of 80 % to meet the standard requirement for base material designed by DOH, Thailand (DH-S201/2544). The CBR of LS, RCA, and SS was 18, 43, and 58 %, respectively, and lower than the minimum requirement; hence the cement is used to stabilize these materials following the DOH, Thailand guideline for cement stabilization of base materials.

Ordinary Portland cement having 7-day and 28-day compressive strengths of 24.7 MPa and 32.6 MPa, respectively, was used in this research. Natural rubber latex (NRL) in a liquid form comprised total solid content of 33.06, dry rubber content of 30.8, sludge content of 2.46, and coagulum content of 0.024 percent by weight, which is classified as the low category rubber latex. The specific gravity and pH of NRL were 0.96 and 8, respectively.

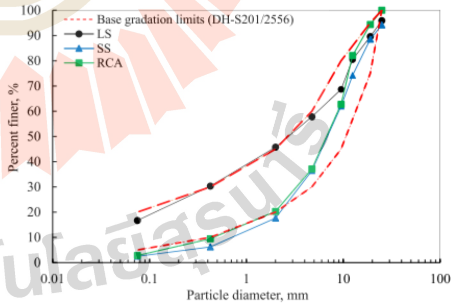


Fig. 1. Grain size distribution of LS, SS, and RCA.

Samples preparation

The air-dried LS, SS, and RCA materials were passed through a 19-mm sieve to remove coarser particles before being used in this research. In this study, LS was replaced with 70 % and 50 % of recycled aggregates to design four blends, namely 70SS:30LS, 50SS:50LS, 70RCA:30LS, and 50RCA:50LS. The cement content (5 % by weight) was used for the cement stabilization. Each blend was thoroughly mixed with cement and followed by water to manufacture cement-stabilized SS/RCA:LS samples. Similarly, the blends were mixed with uniform water-NRL liquid to manufacture cement-NRL stabilized SS/RCA:LS samples. The samples were prepared by compaction at maximum dry density (MDD) and optimum liquid content (OLC) in a cylindrical mold with dimensions of 101.6 mm in diameter and 63.5 mm in height, which were predetermined from the modified compaction test [6]. The samples along with the mold were kept in a controlled temperature room (humidity of 95 % and temperature of 25 °C) for 24 h before being demolded and wrapped with the plastic sheet. After 28 days of curing, the samples were subjected to the mechanical strength and fatigue tests. The mechanical strength tests included UCS and ITS, while the fatigue tests included indirect tensile resilient modulus and indirect tensile fatigue. The mixed design showing the ingredient of the studied materials is demonstrated in Table 1.

Laboratory experimental program

The main laboratory program consisted of resilient modulus and fatigue tests on cylindrical samples by applying indirect tensile loads at a temperature of 25 °C using an universal test machine (Fig. 2).

Indirect tensile resilient modulus (IT M_r)

IT M_r test is commonly performed based on ASTM D4123 [7] to measure the relative quality of materials for pavement design and analysis. The test was carried out on cylindrical samples of 101.6 mm in diameter and 63.5 mm in height using UTM under the indirect tension mode. The applied load frequency is 1 Hz with a test duration of 0.1 s and a rest period of 0.9 s. Based on ASTM D4123, the applied load range is from 10 % to 50 % of the ITS value, and a minimum of 50 to 200 load repetitions are recommended for determining the resilient modulus. In this research, 150 pulses of repetitions were determined at a stress level of 30 % of ITS, as suggested by Fedrigo, Núñez, Castañeda López, Kleinert, and Ceratti [26]. The average of the last five values of elastic stiffness after the first 100 cycles is defined as IT M_r. Three samples of each mixture were tested under the same condition, and the average was presented as IT M_r, which was calculated based on the following equation:

$$ITM_r = \frac{P(v + 0.27)}{t\Delta h} \quad (1)$$

where IT M_r is the indirect tensile resilient modulus (MPa), P is the repeated load (N), v is the Poisson's ratio (assumed to be 0.35), t is the sample thickness, and Δh is the total horizontal recoverable deformation (mm).

Indirect tensile fatigue (ITF)

ITF test is conducted to assess the fatigue resistance of cement-stabilized materials. Either controlled stress (load) or controlled strain (displacement) is used in the fatigue test. In the controlled stress fatigue testing, the applied stress is kept constant, and the strain gradually increases, which is suitable for lightly cement stabilized material. While a constant strain is kept constant for the controlled strain testing mode. In this study, an indirect tensile fatigue test is carried out in controlled stress mode by EN 12697 [15].

In the BS EN 12697–24 standard, the fatigue life is defined as the total number of loading cycles needed to fail the sample. The tensile strain at the center of the sample is calculated with the equation:

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

where Poisson's ratio (v) is assumed as equal to 0.35, hence equation (2) becomes:

$$\varepsilon_0 = 2.1\frac{\Delta H}{d} \quad (3)$$

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

$$\varepsilon_p = 2.1\frac{\Delta p}{d} \quad (4)$$

where ε_p is the tensile plastic strain at the center of the sample (μ_ε), and Δp is the initial plastic deformation (mm), and d is the sample diameter (mm).

Table 1
The ingredient of mixed design in this study.

Mixtures	SS (%)	RCA (%)	LS (%)	r/c* ratio
SS:LS = 70:30, r/c = 0 %	70	0	30	0
SS:LS = 70:30, r/c = 3 %	70	0	30	3
SS:LS = 70:30, r/c = 5 %	70	0	30	5
SS:LS = 70:30, r/c = 10 %	70	0	30	10
SS:LS = 70:30, r/c = 15 %	70	0	30	15
SS:LS = 50:50, r/c = 0 %	50	0	50	0
SS:LS = 50:50, r/c = 3 %	50	0	50	3
SS:LS = 50:50, r/c = 5 %	50	0	50	5
SS:LS = 50:50, r/c = 10 %	50	0	50	10
SS:LS = 50:50, r/c = 15 %	50	0	50	15
RCA:LS = 70:30, r/c = 0 %	0	70	30	0
RCA:LS = 70:30, r/c = 3 %	0	70	30	3
RCA:LS = 70:30, r/c = 5 %	0	70	30	5
RCA:LS = 70:30, r/c = 10 %	0	70	30	10
RCA:LS = 70:30, r/c = 15 %	0	70	30	15
RCA:LS = 50:50, r/c = 0 %	0	50	50	0
RCA:LS = 50:50, r/c = 3 %	0	50	50	3
RCA:LS = 50:50, r/c = 5 %	0	50	50	5
RCA:LS = 50:50, r/c = 10 %	0	50	50	10
RCA:LS = 50:50, r/c = 15 %	0	50	50	15

* 5% cement content by weight.

Results and Discussion

Mechanical strength

Fig. 3**a and 3b**, respectively, illustrate the 28-day UCS and ITS of cement- and cement-NRL stabilized SS/RCA:LS blends at different SS/RCA:LS replacement ratios and dry rubber/cement (r/c) ratios. Fig. 3**a** demonstrates that the highest UCS of cement-NRL stabilized SS:LS blends was found at an r/c ratio of 3 % and was higher than that of cement-stabilized SS:LS blends at both SS:LS = 70:30 and SS:LS = 50:50. While the r/c ratio of 5 % was found to provide the highest UCS of cement-NRL stabilized RCA:LS blends and higher than the cement-stabilized RCA:LS blends at both RCA:LS = 70:30 and RCA:LS = 50:50. As such, the r/c ratios of 3 % and 5 % were considered as the optimum r/c ratios for cement-NRL stabilized SS:LS and RCA:LS blends. For both SS:LS and RCA:LS blends, the cement-NRL stabilized samples contained higher recycled material replacement ratio indicated higher UCS values at a particular r/c ratio. This might be because both recycled materials (SS and RCA) had better mechanical properties than LS. For instance, SS had a higher resistance to Los Angeles abrasion than RCA and LS, respectively.

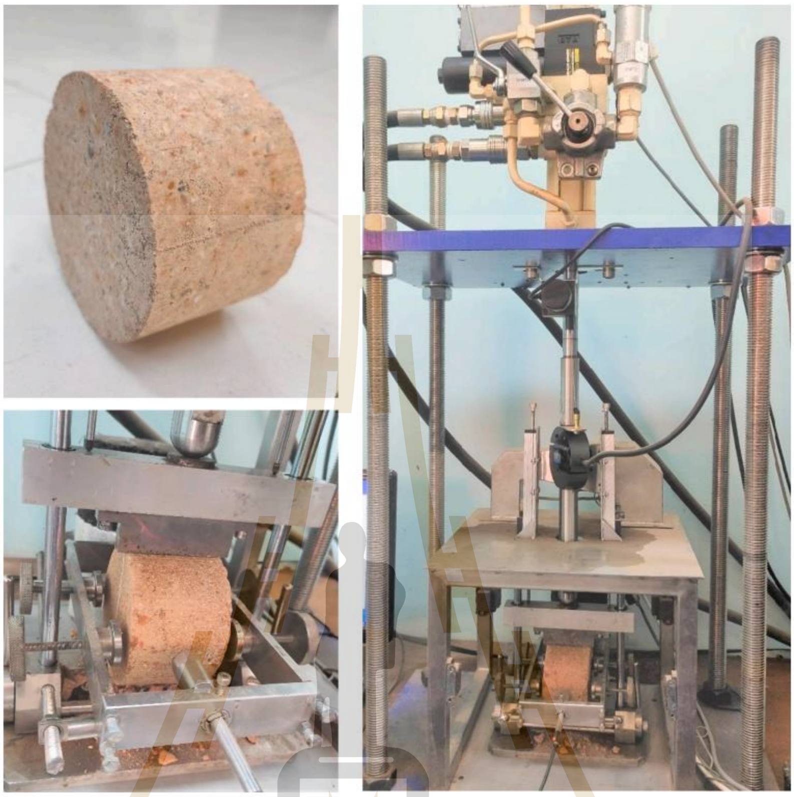


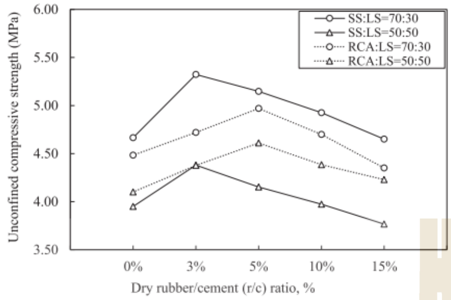
Fig. 2. Photograph of cylindrical samples and testing equipment in this research.

The trends of ITS results of cement-NRL stabilized SS:LS blends and RCA:LS blends were noticeably similar to those of UCS results. This indicates that the additional NRL can improve both compressive and tensile strengths of cement-stabilized SS/RCA:LS blends, which provide advantages for using these bound materials as a pavement base course. Farhan et al. [25] proved that the high tensile strength of cement-stabilized material could improve pavement service life as it mitigates the fatigue cracking of the asphalt surface, which is a significant cause of pavement failure. A microstructural analysis using scanning electron microscope from the previous authors' research indicated that at the optimum r/c ratio, the NRL polymer films could enhance the interparticle bonding of cement-stabilized recycled material [59], which is similar to the other research on cement-NRL stabilized soil material [17–18,37]. On the other hand, the excessive NRL used in cement-stabilized materials exhibits a negative effect on its microstructural properties as the thick NRL films retard the cement hydration, resulting in the low mechanical strength of cement-NRL stabilized materials.

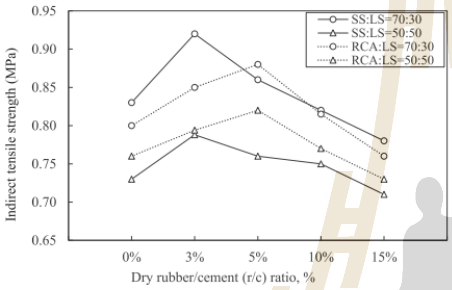
Indirect tensile resilient modulus (IT M_r)

Fig. 4 summarizes the IT M_r values of cement- and cement-NRL stabilized SS:LS and RCA:LS blends at different SS/RCA replacement ratios and various r/c ratios. Similar to UCS and ITS results, the IT M_r of cement-NRL stabilized SS:LS and RCA:LS blends at both SS/RCA:LS replacement ratios increased with an increase of r/c ratio until the highest values at the optimum r/c ratios and then decreased. The highest IT M_r values of cement-NRL stabilized SS:LS blends and RCA:LS blends were found at the optimum r/c ratios of 3 % and 5 %, respectively, which were higher than those of cement-stabilized SS:LS and RCA:LS blends. The IT M_r values of cement-NRL stabilized SS:LS = 70:30 and SS:LS = 50:50 samples at optimum r/c ratio = 3 % were 20 % and 24 % higher than those of cement-stabilized SS:LS = 70:30 and SS:LS = 50:50 samples, respectively. While the IT M_r values of cement-NRL RCA:LS = 70:30 and RCA:LS = 50:50 samples at optimum r/c ratio = 5 % were increased by 17 % and 22 % compared with those of cement-stabilized RCA:LS = 70:30 and RCA:LS = 50:50 samples, respectively. It implied that the NRL additive enhanced mechanical strength and cyclic stiffness properties.

For a particular type of recycled material, the samples with 70 % of recycled material replacements (SS:LS = 70:30 and RCA:LS = 70:30) had higher IT M_r values than those with 50 % recycled material replacements (SS:LS = 50:50 and RCA:LS = 50:50) at the same r/c ratio. Furthermore, at the optimum r/c ratio, cement-NRL stabilized SS:LS blends exhibited higher IT M_r values than cement-NRL stabilized RCA:LS



(a)



(b)

Fig. 3. (a) Unconfined compressive strength, and (b) Indirect tensile strength of 28-day cement- and cement-NRL stabilized SS:LS and RCA:LS samples at different SS/RCA:LS replacements and dry rubber/cement (r/c) ratios.

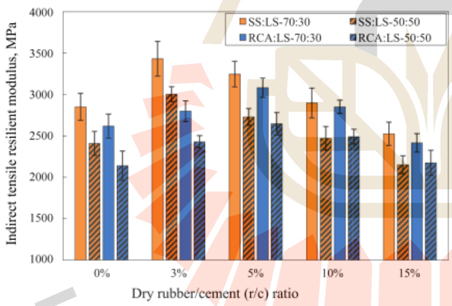


Fig. 4. Indirect tensile resilient modulus of cement- and cement-NRL stabilized SS:LS and RCA:LS blends at different SS/RCA replacements and dry rubber/cement (r/c) ratios.

blends. This can be attributed to the mechanical and physical properties of SS were superior to those of RCA and LS, respectively. For instance, SS had LA abrasion = 17.2 %, CBR = 58 %, and flakiness index = 3.20, RCA had LA abrasion = 31 %, CBR = 43 %, and flakiness index = 8.92, while LS had LA abrasion = 34 %, and CBR = 18 %. From the previous similar research, the mechanical and physical properties of the materials were found to influence the resilient modulus of cement-stabilized recycled waste materials [5,22].

Following local and international road authorities such as AUSTROADS and ASSHTO guidelines for mechanistic-empirical pavement design, the pavement structure layers were evaluated by the resilient modulus [1,23,34]. Resilient modulus is a vital pavement design parameter (measurement indicator) of a material's deflection characteristic; the design thickness depends on the resilient modulus. In addition, pavement service life is significantly related to distress failures, including fatigue cracking and rutting mechanism of pavement structures. In order words, the high resilient modulus of the cement-NRL stabilized base layers can enhance the resistance against the fatigue cracking and rutting failure of the pavement under cyclic loading. NRL additive can enhance the resilient modulus of cement-stabilized SS/RCA:LS blends, which means the pavement service life might be extended when used these materials in the pavement structures.

Resilient modulus is a critical mechanistic property of a material described from a stress–strain relationship, which is similar in concept to the modulus of elasticity. However, the difference is that the modulus of elasticity is determined from the static load (general stress–strain relationship). In contrast, the resilient modulus is determined from the cyclic load (cyclic stress–strain relationship). Hence, the resilient modulus is defined as the stress amplitude (applied load per area of the specimen) proportional to strain amplitude (recoverable deformation compared to its original height). Based on the cyclic stress–strain relationship, the stress and strain increase as the load is applied. However, when the stress is reduced, the strain also reduces, but not all strain is recovered after the stress is removed. In other words, the total horizontal deformation is the sum of elastic deformation or recoverable deformation (resilient behavior) and plastic deformation or permanent deformation (absorbing behavior).

Since the pavement's service life is significantly associated with the pavement structure deformation, the horizontal deformations versus the number of cycles behaviors of cement- and cement-NRL stabilized SS/RCA:LS blends were examined in this research. Fig. 5 demonstrates the relationship between horizontal deformations and the number of cycles under load repetitions at 30 % stress level of cement- and cement-NRL stabilized 70SS:30LS, 50SS:50SS, 70RCA:30LS, and 50RCA:50LS samples at optimum r/c ratios. It is of interest to demonstrate that the horizontal deformations versus the number of cycles relationship of cement- and cement-NRL stabilized SS:LS blends and RCA:LS blends at all recycled material replacement ratios were similar. The NRL additive significantly reduced the horizontal deformations (total, elastic, and plastic deformations) of cement stabilized SS/RCA:LS blends.

Several researchers found that the density increase could enhance the resistance to permanent deformation of materials under repetitive loading. Elliott and Thornton [23] and Hall et al. [30] reported that the density of the granular base materials notably influenced the resilient modulus, and the high density could significantly reduce the plastic strain (permanent deformation). The samples under 95 % compaction effort exhibited remarkably large permanent axial strain when compared with the samples under 100 % compaction [11]. Allen [3] also reported that the plastic strain of the compacted crushed limestone and gravel aggregate under the Proctor energy was respectively reduced by approximately 80 % and 20 % when they were subjected to the modified Proctor energy. In this study, the cement-NRL stabilized SS:LS and RCA:LS blends at optimum r/c ratio had a higher density than cement-stabilized SS:LS and RCA:LS blends at the same compaction energy. The NRL films can enhance the interparticle bonding of the compacted cement-stabilized SS/RCA:LS blends and the mechanical strength (UCS and ITS) properties, which lead to the improvement of resilient modulus. The high resilient modulus and low permanent deformation of cement-NRL stabilized SS/RCA:LS blends are associated with the improvement of the pavement structure capacity against fatigue rutting failure. As such, the pavement life might last longer as similar to the study on the cement-NRL stabilized soil [60].

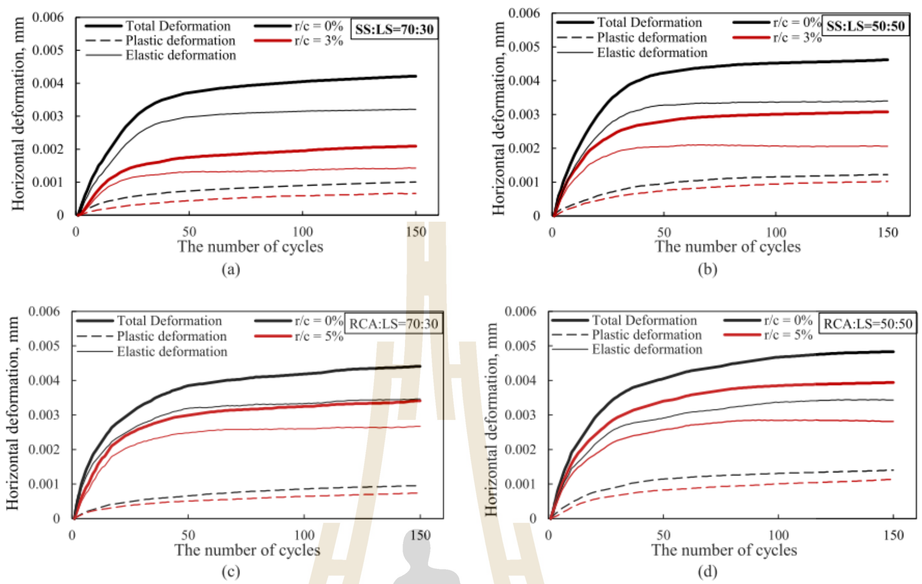


Fig. 5. Relationship between horizontal deformations and the number of cycles under repeated-load at 30 % stress level of cement- and cement-NRL stabilized SS/RCA:LS blends at optimum r/c ratio: (a) SS:LS = 70:30, SS:LS = 50:50, (c) RCA:LS = 70:30, and (d) RCA:LS = 50:50.

Indirect tensile fatigue life

The typical relationship between the number of cycles and the deformation of a sample under cyclic loading is divided into three zones (Fig. 6). The first zone expresses the rapid development rate of deformation with a small number of cyclic loadings; the second zone represents the gradual development of deformation with the linear increase of the number of cycles. The accumulated micro-cracks are formed and gradually developed during the first and the second zones, leading to the sudden failure of the sample in the third zone [38,44]. Following EN 12697 [15], indirect tensile fatigue life (ITFL) is defined as the number of cycles (F_n) at the fracture point of the sample under the cyclic load test.

Fig. 7 illustrates the relationship between the number of cycles and

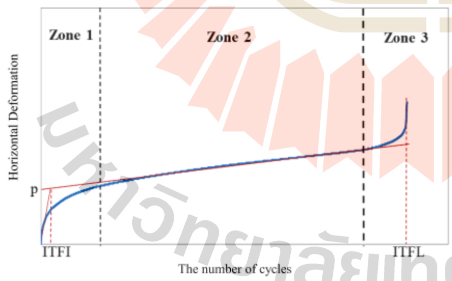


Fig. 6. The schematic plot of the relationship between horizontal deformation and the number of cycles.

horizontal deformation under the fatigue test at 70 % stress level of cement- and cement-NRL stabilized SS:LS and RCA:LS blends at different r/c ratios. Furthermore, Fig. 8 summaries the fatigue life of cement- and cement-NRL stabilized SS:LS and RCA:LS blends at different recycled material replacement ratios and different r/c ratios. For a particular type of recycled material, the fatigue life results were consistent with the resilient modulus results in that the cement-NRL stabilized SS:LS blends at an optimum ratio of 3 % and RCA:LS blends at an optimum ratio of 5 % indicated the highest fatigue life. At the optimum r/c ratios, the cement-NRL stabilized SS/RCA:LS blends had fatigue life about 2 to 3 times higher than the cement-stabilized SS/RCA:LS blends. It implies that the NRL additive can improve the resilient modulus and enhance the fatigue life of the cement-NRL stabilized SS/RCA:LS blends under repeated loading. This might be attributed to the cement and blended materials matrix formed during the hydration process was reinforced by the NRL film formation, resulting in the strength development [47]. In addition, Tran et al. [59] indicated that the NRL films could also fill the pore spaces between the cement and blended materials matrix, leading to bonding strength enhancement and porosity reduction. This is in agreement with the research conducted on the cement-treated sand by Festugato et al. [27], in that the resilient modulus and fatigue life increased with the decrease of porosity of cement stabilized materials. However, beyond the optimum r/c ratio, the cyclic properties of cement-NRL stabilized materials were reduced as the excessive amount of NRL retards the cement hydration process; hence the decrease of cement hydration products (C—S—H) is [17,59].

Meanwhile, the cement-NRL stabilized SS:LS blends had higher fatigue life than the cement-NRL stabilized RCA:LS blends at the same replacement ratio and r/c ratio. For cement-stabilized SS:LS and RCA:LS blends, the fatigue life of SS:LS = 70:30, SS:LS = 50:50, RCA:LS = 70:30, and RCA:LS = 50:50 reached 1567, 531, 425, and 378 cycles, respectively. At an optimum r/c ratio of 3 %, the cement-NRL stabilized SS:LS

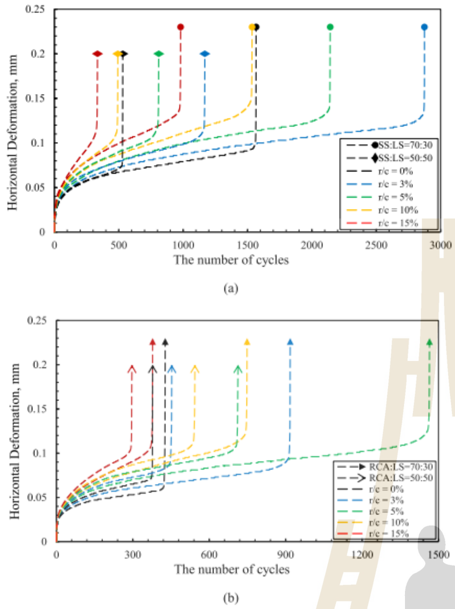


Fig. 7. Relationship between the number of cycles and horizontal deformation under fatigue test at 70% stress level: (a) cement- and cement-NRL stabilized SS:LS blends, (b) cement- and cement-NRL stabilized RCA:LS blends at different r/c ratios.

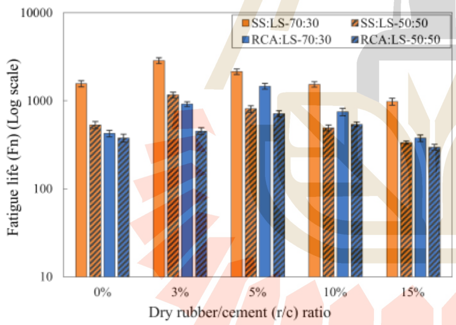


Fig. 8. ITFL of cement- and cement-NRL stabilized SS:LS and RCA:LS blends at different SS/RCA replacements and r/c ratios.

= 70:30 and SS:LS = 50:50 had a fatigue life of 2865 and 1168 cycles, respectively. At an optimum r/c ratio of 5 %, the cement-NRL stabilized RCA:LS = 70:30 and RCA:LS = 50:50 had a fatigue life of 1465 and 714 cycles, respectively. Besides the influence of NRL additive, the engineering and physical properties of aggregates might influence the mechanical strength (UCS and ITS) and the resistance to the fatigue loading of cement-NRL stabilized SS:LS and RCA:LS blends. The resistance to Los Angle abrasion, CBR, and flakiness index of SS were superior to those of RCA, and LS, respectively in this study, which is also similar to the previous finding [56,59]. As a result, the cement-NRL stabilized SS/RCA:LS blends with 70 % recycled material replacement ratio indicated high fatigue life than the samples with 50 % recycled material replacement ratio.

Fig. 9 demonstrates the relationship between the number of cycles and horizontal deformations of cement-stabilized SS/RCA:LS blends and cement-NRL stabilized SS:LS blends at an optimum ratio of 3 % and RCA:LS blends at an optimum ratio of 5 % under cyclic loading at 70 % stress level. It is interesting to note that the total horizontal deformations of cement-NRL stabilized SS/RCA:LS blends at both 70 % and 50 % recycled material replacement ratios were higher than cement-stabilized SS/RCA:LS blends at 70 % stress level. It is different from the results shown in Fig. 5 in that the total deformations of cement-NRL stabilized SS/RCA:LS blends at both 70 % and 50 % recycled material replacement ratios at 70 % stress level were lower than those of cement-stabilized SS/RCA:LS blends at 30 % stress level. However, the plastic deformations of cement-NRL stabilized SS/RCA:LS blends at optimum r/c ratios with all recycled material replacement ratios were lower than those of cement-NRL stabilized SS/RCA:LS blends under both 30 % and 70 % stress levels. Gnanendran and Piratheepan [29] reported a similar degree of plastic deformation of the cement-stabilized soil at a 50 % – 75 % stress level. The accumulated plastic deformation in granular-based and subbase layers was found to be one of the most important causes of severe rutting development at the pavement surface and led to the failure of pavement serviceability under cyclic traffic load [39,46,62]. This confirmed that the NRL additive crucially contributed to the improvement of fatigue life and reduced the permanent deformation of cement-stabilized recycled materials as a pavement base course under repeated traffic load.

In addition, the relationship between the number of cycles and horizontal deformations in Fig. 9 clearly indicated the sudden failure of cement-stabilized SS/RCA:LS blends at all recycled material replacement ratios, demonstrating the brittle behavior when compared with that samples with additional NRL additive. It implies that the additional NRL polymer additive can improve the ductility behavior of cement-stabilized recycled materials. Vo and Plank [61] reported that the NRL films are a bridge to transfer the tensile stress to the particles and prevent sudden failure. The positive role of NRL in improving the brittle behavior of cement-stabilized SS:LS and RCA:LS under compressive loading was also proved in the previous study, in which the failure strain of cement-NRL stabilized samples increased with an increase of r/c ratio [59].

Permanent deformation and Fatigue Model

In general, permanent deformation is one of the essential types of repeated load-associated distresses (fatigue cracking and rutting) occurring in the pavement structure. The pavement designers and engineers concern about fatigue cracking and rutting effect on the lateral and longitudinal profiles at the pavement surface. This distress failure can reduce the pavement's service life and significant safety pavement user's concern. The pavement deformation is associated with rutting and fatigue cracks gradually developing with accumulated load repetitions. In addition, the variation of rut depth is a crucial factor affecting road roughness and serviceability. In recent years, the M−E pavement design guide has become a state-of-the-practice approach for designing and analyzing pavement structures based on the mechanistic-empirical principles. This is because of M−E approaches determined the pavement responses, including stress, strains, and deformations, and applied those responses to determine the accumulated damage over time under the repeated load. Hence, many researchers carried out fatigue tests to evaluate the fatigue properties of the unbound and bound materials, including cement-stabilized lateritic soil and cement-stabilized granular and recycled aggregates [13,22,36,48,49]. However, no study was found on fatigue characteristics of cement-NRL stabilized recycled materials, which is the important objective of this research. The fatigue

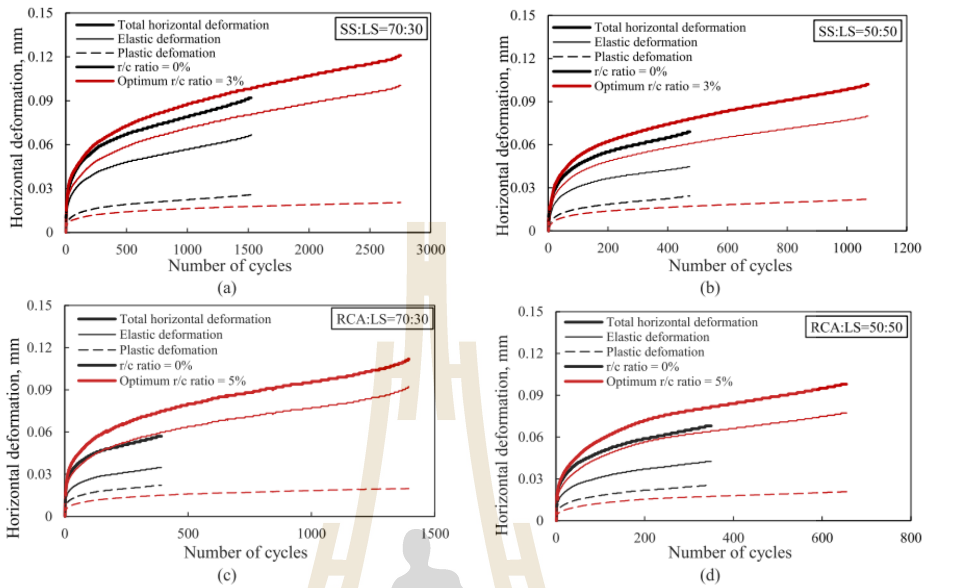


Fig. 9. Relationship between horizontal deformations and the number of cycles under repeated-load at 70 % stress level of cement- and cement-NRL stabilized SS/RCA:LS blends at optimum r/c ratio: (a) SS:LS = 70:30, SS:LS = 50:50, (c) RCA:LS = 70:30, and (d) RCA:LS = 50:50.

properties test conducted to determine the resilient modulus, fatigue life, and permanent deformation is incredibly time-consuming and complicated to perform, resulting in a lack of a prediction model for implementation. Therefore, this research proposed those fatigue properties associated with the conventional strength properties of the cement- and cement-NRL stabilized SS:LS and RCA:LS blends as sustainable pavement base materials. The following steps are involved in selecting the fatigue properties of the studied materials.

Step 1. Develop a relationship between UCS and ITS of cement- and cement-NRL stabilized SS:LS and RCA:LS blends at different recycled replacement ratios and r/c ratios (Fig. 10).
Step 2. The resilient modulus was performed based on the indirect tensile test. Hence, it is easy to determine the resilient modulus of the studied materials based on the resilient modulus versus ITS relationship as shown in Fig. 11.
Step 3. Similar to the determination procedure of resilient modulus, the fatigue life of the studied materials was performed based on the indirect tensile test under cyclic load conditions. The predicted fatigue life of the studied materials can be determined from a relationship between fatigue life and resilient modulus, as depicted in Fig. 12.
Step 4. Develop a relationship between permanent deformation and fatigue life of the studied materials (Fig. 13). Based on this relationship, the permanent deformation of the studied materials is estimated to be associated with the number of cycles. In other ways, the permanent deformation model can predict the rutting distress in the pavement base layer.

Previous studies [59] and [21] demonstrated the linear relationship between unconfined compressive strength and indirect tensile strength. In this study, however, the polynomial correlations between UCS versus ITS, ITS versus IT M_r, IT M_r versus F_n, and F_n versus PD were found to be the best with very high coefficient of determination.

Conclusions

This research investigated the influence of NRL additive on the resilient modulus and fatigue properties of cement-stabilized lateritic soil with recycled materials (SS and RCA) replacements. Four blends included SS:LS = 70:30, SS:LS = 50:50, RCA:LS = 70:30, and RCA:LS = 50:50, and 5 % cement content by weight were designed for this research. To investigate the influence of NRL additive on cement-stabilized SS/RCA:LS blends, the dry NRL to cement (r/c) were designed to be 0 %, 3 %, 5 %, 10 %, and 15 %. The mechanical strength properties (UCS and ITS) and the fatigue properties including indirect tensile resilient modulus (IT M_r) and fatigue life of the studied materials under indirect tensile force were investigated. The following conclusions can be drawn:

1. The r/c ratios of 3 % and 5 % were found to be the optimum r/c ratio for cement-NRL stabilized SS:LS blends and RCA:LS blends, respectively that produce the highest UCS, ITS, IT M_r, and fatigue life, which were higher than those of cement-stabilized SS:LS blends and RCA:LS blends for all recycled material replacement ratios. This is because the cement-blended materials matrix formed during the hydration process was reinforced by NRL film formation, resulted in a dense matrix and strength development. However, beyond the optimum r/c ratio, the excessive amount of NRL generated thick NRL films and retarded the cement hydration products, resulting in low-strength development.
2. Overall, the cement-NRL stabilized SS:LS blends exhibited higher mechanical strength properties and fatigue properties than the cement-NRL stabilized RCA:LS blends. In addition, for both types of

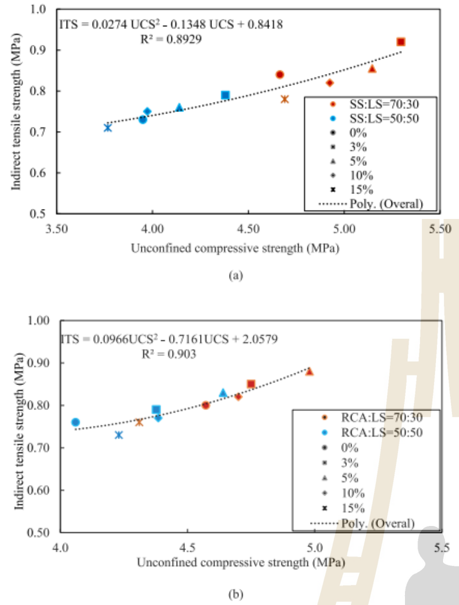


Fig. 10. Relationship between UCS and ITS of SS:LS (a) and RCA:LS (b) samples at different r/c ratios.

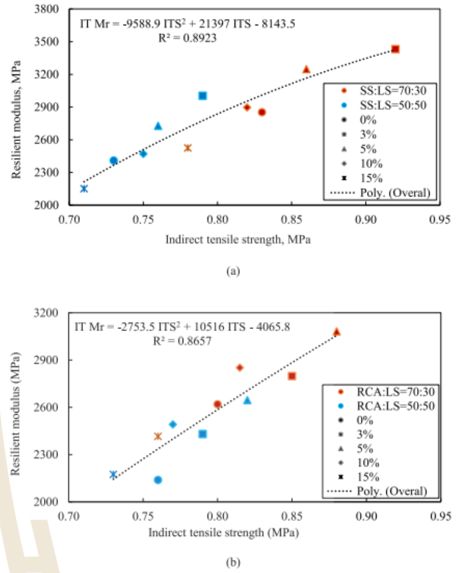


Fig. 11. Relationship between ITS and IT M_r of SS:LS (a) and RCA:LS (b) samples at different r/c ratios.

recycled materials, the cement-NRL stabilized SS/RCA:LS blends contained 70 % recycled material replacement ratio exhibited superior mechanical strength and fatigue properties than the samples contained 50 % recycled material replacement ratio. This is attributed to SS having higher mechanical and physical properties including LA abrasion, CBR, and flakiness index than RCA and LS, respectively. It implied that besides the effluence of NRL additive, the good mechanical and physical properties of aggregates attribute to the mechanistic and fatigue properties of cement-NRL stabilized soil with recycled material replacement ratios.

3. The relationship between the number of cycles and horizontal deformations under indirect tensile load repetitions demonstrated that the cement-stabilized SS/RCA:LS blends exhibited brittle behavior and the sudden failure occurred at the low number of cycles. The additional NRL additive can improve the ductility of cement-stabilized SS/RCA:LS blends. At the optimum r/c ratios, the cement-NRL stabilized SS/RCA:LS blends had higher fatigue life and lower permanent deformation (permanent deformation) at both 30 % and 70 % stress levels. The NRL additive can lubricate the compacted particles and increase the density and lower permanent deformation. Furthermore, the NRL films act as the bridge to transfer the tensile stress to particles and prevent the sudden failure of cement-NRL stabilized SS/RCA:LS blends.

The research outputs confirmed that NRL additive could improve the mechanistic and fatigue properties cement-stabilized soil with recycled material replacements, which enhance the service of the pavements under cyclic traffic loads. The mechanistic and fatigue models of cement- and cement-NRL stabilized soil with recycled material replacements are proposed and they are important for the pavement designers and engineers when using mechanistic-empirical (M–E)

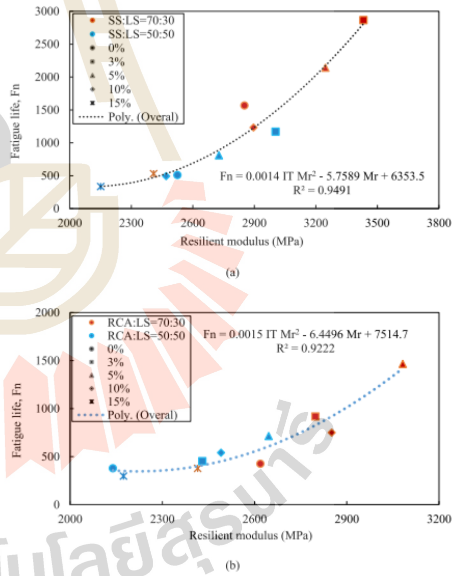


Fig. 12. Relationship between IT M_r and Fatigue life of SS:LS (a) and RCA:LS (b) samples at different r/c ratios.

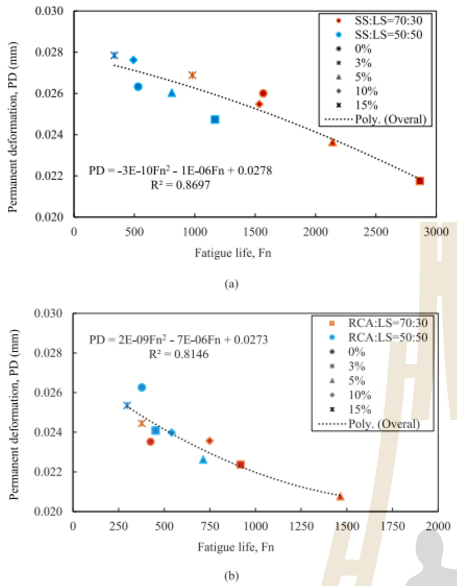


Fig. 13. Relationship between Fatigue life and Permanent deformation of SS:LS (a) and RCA:LS (b) samples at different r/c ratios.

pavement design approach. A numerical analysis based on the present experimental results is recommended for future study to develop the distress model for predicting the fatigue cracking life of the pavement structure when using cement-NRL stabilized recycled aggregates as the base materials.

CRediT authorship contribution statement

Menglim Hoy: Project administration, Supervision, Conceptualization, Funding acquisition, Writing – original draft, Methodology. **Ngoc Quynh Tran:** Formal analysis, Methodology, Writing – original draft. **Apichat Suddeepong:** Methodology, Conceptualization. **Suksun Horpibulsuk:** Supervision, Funding acquisition, Methodology, Writing – review & editing. **Manlika Mobkrathok:** Methodology, Writing – original draft. **Avirut Chinkulkijniwat:** Supervision, Funding acquisition, Methodology, Writing – review & editing. **Arul Arulrajah:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was financially supported by the National Science and Technology Development Agency under the Chair Professor program Grant No. P-19-52303, Suranaree University of Technology and Thailand Science Research and Innovation (TSRI). This research project was also funded by National Research Council of Thailand (NRCT) under Young Researcher Genius Program Grant No. N42A650210. The 4th and last authors gratefully acknowledge the support from the Australian Research Council (Project Number LP200301154).

References

[1] AASHTO. Mechanistic-Empirical pavement design guide: A manual of practice. American Association of State Highway and Transportation Officials; 2015.
[2] Agrela F, Barbudo A, Ramírez A, Ayuso J, Carvajal MD, Jiménez JR. Construction of road sections using mixed recycled aggregates treated with cement in Malaga, Spain. Resour Conserv Recycl 2012;58:98–106. https://doi.org/10.1016/j.resconrec.2011.11.003.
[3] Allen J. The Effect of Non-Constant Lateral Pressures of the Resilient Response of Granular Materials. Urbana, Illinois: Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign; 1973. Ph.D. dissertation.
[4] Arora S, Aydilek AH. Class F Fly-Ash-Amended Soils as Highway Base Materials. J Mater Civ Eng 2005;17:640–9. https://doi.org/10.1061/(ASCE)0899-1561(2005)17:6(640).
[5] Arulrajah A, Perera S, Wong YC, Horpibulsuk S, Maghool F. Stiffness and flexural strength evaluation of cement stabilized PET blends with demolition wastes. Constr Build Mater 2020;239. https://doi.org/10.1016/j.conbuildmat.2019.117819.
[6] ASTM-D1557. Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3 (2,700 kN-m/m^3)). West Conshohocken, PA: ASTM; 2012.
[7] ASTM-D4123. Indirect Tension test for Resilient Modulus of Bituminous Mixtures. West Conshohocken, PA: ASTM; 1995.
[8] Baghini MS, Ismail A, Karim MRB. Evaluation of cement-treated mixtures with slow setting bitumenemulsion as base course material for road pavements. Constr Build Mater 2015;94:323–36. https://doi.org/10.1016/j.conbuildmat.2015.07.057.
[9] Baghini MS, Ismail A, Naseralavi SS, Firoozi AA. Performance evaluation of road base stabilized with styrene–butadiene copolymer latex and Portland cement. Int J Pavement Res Technol 2016;9(4):321–36. https://doi.org/10.1016/j.ijprt.2016.08.006.
[10] Barišić I, Dimter S, Rukavina T. Elastic properties of cement-stabilised mixes with steel slag. Int J Pavement Eng 2015;17(9):753–62. https://doi.org/10.1080/10298436.2015.1019496.
[11] Barksdale RD. Laboratory Evaluation of Rutting in Base Course Materials. In: Proceedings of the 3rd International Conference on the Structural Design of Asphalt Pavements 1972; 1: 161-174.
[12] Bhogal BS, Coupe PS, Davies J, Fendukly LM. Dynamic flexure tests of soil-cement beams. J Mater Sci Lett 1995;14:302–4.
[13] Biswal DR, Sahoo UC, Dash SR. Fatigue Characteristics of Cement-Stabilized Granular Lateritic Soils. J Transport Eng, Part B: Pavements 2020;146(1): 04019038. https://doi.org/10.1061/JPEODX.0000147.
[14] Biswal DR, Sahoo UC, Dash SR. Fatigue Characteristics of Cement-Stabilized Granular Lateritic Soils. J Transport Eng, Part B: Pavements 2020;146(1). https://doi.org/10.1061/jpeodx.0000147.
[15] BS-EN-12697-24. Bituminous mixtures - Test methods for hot mix asphalt; 2012.
[16] Bullen F. The resilient moduli of cement treated materials. Road Transport Res 1994;3.
[17] Buritatum A, Suddeepong A, Horpibulsuk S, Udomchai A, Arulrajah A, Mohammadinia A, Hoy M. Improvement of Tensile Properties of Cement-Stabilized Soil Using Natural Rubber Latex. J Mater Civ Eng 2022;34(4). https://doi.org/10.1061/(ASCE)MT.1943-5533.0004173.
[18] Buritatum A, Takaikaew T, Horpibulsuk S, Udomchai A, Hoy M, Vichitcholchai N, Arulrajah A. Mechanical Strength Improvement of Cement-Stabilized Soil Using Natural Rubber Latex for Pavement Base Applications. Mater Civil Eng 2020;32 (12). https://doi.org/10.1061/(ASCE)MT.1943-5533.0003471.
[19] Chakravarthi S, Boyina A, Singh AK, Shankar S. Evaluation of cement treated reclaimed asphalt pavement and recycled concrete pavement bases. Int J Pavement Res Technol 2019;12(6):581–8. https://doi.org/10.1007/s42947-019-0069-1.
[20] Christopher B, Schwartz C, Boudreau R. Geotechnical Aspects of Pavements Reference Manual. Woodbury: Federal Highway Administration; 2006.
[21] Consoli NC, Marques SFV, Floss MF, Festugato L. Broad-Spectrum Empirical Correlation Determining Tensile and Compressive Strength of Cement-Bonded Clean Granular Soils. J Mater Civ Eng 2017;29(6). https://doi.org/10.1061/(asce)mt.1943-5533.0001858.
[22] Disfani MM, Arulrajah A, Haghighi H, Mohammadinia A, Horpibulsuk S. Flexural beam fatigue strength evaluation of crushed brick as a supplementary material in cement stabilized recycled concrete aggregates. Constr Build Mater 2014;68: 667–76. https://doi.org/10.1016/j.conbuildmat.2014.07.007.
[23] Elliott RP, Thornton SI. Resilient modulus and AASHTO pavement design. Transp Res Rec 1988:1196.
[24] Estabragh AR, Beytolahpour I, Javadi AA. Effect of Resin on the Strength of Soil-Cement Mixture. Mater Civ Eng 2011;23(7):969–76. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000252.
[25] Farhan AH, Dawson AR, Thom NH, Adam S, Smith MJ. Flexural characteristics of rubberized cement-stabilized crushed aggregate for pavement structure. Mater Des 2015;88:897–905. https://doi.org/10.1016/j.matdes.2015.09.071.

[26] Fedrigo W, Núñez WP, Castañeda López MA, Kleinert TR, Ceratti JAP. A study on the resilient modulus of cement-treated mixtures of RAP and aggregates using indirect tensile, triaxial and flexural tests. Constr Build Mater 2018;171:161–9. https://doi.org/10.1016/j.conbuildmat.2018.03.119.

[27] Festugato L, Venson GI, Consoli NC. Parameters controlling cyclic behaviour of cement-treated sand. Transp Geotech 2021;27. https://doi.org/10.1016/j.trgeo.2020.100488.

[28] Firoozi AA, Guney Olgun C, Firoozi AA, Baghini MS. Fundamentals of soil stabilization. Int J Geo-Eng 2017;8(1):26. https://doi.org/10.1186/s40703-017-0064-9.

[29] Gnanendran CT, Piratheepan J. Characterisation of a lightly stabilised granular material by indirect diametrical tensile testing. Int J Pavement Eng 2008;9(6):445–56. https://doi.org/10.1080/10298430802342732.

[30] Hall KT, Correa CE, Carpenter SH, Elliot RP. Rehabilitation strategies for highway pavements. National Cooperative Highway Research Program, Web Document, 2001; 35.

[31] Horpibulsuk S, Katkan W, Sirilerdwattana W, Rachan L. Strength development in cement stabilized low plasticity and coarse grained soils: Laboratory and field study. Soils Found 2006;46(3).

[32] Horpibulsuk S, Rachan R, Chinkulkijniwat A, Raksachon Y, Suddeepong A. Analysis of strength development in cement-stabilized silty clay from microstructural considerations. Constr Build Mater 2010;24:2011–21.

[33] Imtiaz T, Ahmed A, Hossain MS, Faysal M. Microstructure Analysis and Strength Characterization of Recycled Base and Sub-Base Materials Using Scanning Electron Microscope. Infracstructure 2020;5(070). https://doi.org/10.3390/infrastrures5090070.

[34] Jameson G. Guide to pavement technology: part 2: pavement structural design; 2008.

[35] Jitsangiam P, Nusit K, Chummuneerat S, Chindaprasirt P, Pichayapan P. Fatigue Assessment of Cement-Treated Base for Roads: An Examination of Beam-Fatigue Tests. J Mater Civ Eng 2016;28(10). https://doi.org/10.1061/(asce)mt.1943-5533.0001601.

[36] Jitsangiam P, Nusit K, Chummuneerat S, Chindaprasirt P, Pichayapan P. Fatigue Assessment of Cement-Treated Base for Roads: An Examination of Beam-Fatigue Tests. J Mater Civ Eng 2016;28(10):04016095. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001601.

[37] Jose A, Kasthurba AK. Laterite soil-cement blocks modified using natural rubber latex: Assessment of its properties and performance. Construction and Building Materials; 2020.

[38] Kavussi A, Modarres A. Laboratory fatigue models for recycled mixes with bitumen emulsion and cement. Constr Build Mater 2010;24(10):1920–7. https://doi.org/10.1016/j.conbuildmat.2010.04.009.

[39] Khedr S. Deformation characteristics of granular base course in flexible pavements. Transp Res Rec 1985;1043:131–8.

[40] Khoury N, Zaman MM. Durability of stabilized base courses subjected to wet–dry cycles. Int J Pavement Eng 2007;8(4):265–76. https://doi.org/10.1080/10298430701342874.

[41] Li N, Lv S, Wang W, Guo J, Jiang P, Liu Y. Experimental investigations on the mechanical behavior of iron tailings powder with compound admixture of cement and nano-clay. Constr Build Mater 2020;254. https://doi.org/10.1016/j.conbuildmat.2020.119259.

[42] Li Q, Hu J. Mechanical and Durability Properties of Cement-Stabilized Recycled Concrete Aggregate. Sustainability 2020;12(18). https://doi.org/10.3390/su12187380.

[43] Lv S, Xia C, Liu H, You L, Qu F, Zhong W, Washko S. Strength and fatigue performance for cement-treated aggregate base materials. Int J Pavement Eng 2019;22(6):690–9. https://doi.org/10.1080/10298436.2019.1634808.

[44] Modarres A, Bengar PA. Investigating the indirect tensile stiffness, toughness and fatigue life of hot mix asphalt containing copper slag powder. Int J Pavement Eng 2017;20(8):977–85. https://doi.org/10.1080/10298436.2017.1373390.

[45] Moffat MA, Sharp KG, Vertessy NJ, Johnson-Clarke JR, Vuong BT, Yeo REY. The performance of in situ stabilised marginal sandstone pavements. APRG Rep. No. 22 and ARRB TR Re search Rep. No 322, Australia; 1998.

[46] Mohammad LN, Puppala AJ, Alavilli P. Effect of strain measurements on resilient modulus of sands. ASTM Spec Tech Publ 1994;1213:202.

[47] Muhammad B, Ismail M. Performance of natural rubber latex modified concrete in acidic and sulfated environments. Cem Concr Res 2012;31:129–34. https://doi.org/10.1016/j.conbuildmat.2011.12.099.

[48] Paul DK, Gnanendran CT. Characterization of Lightly Stabilized Granular Base Materials Using Monotonic and Cyclic Load Flexural Testing. J Mater Civ Eng 2016;28(1):04015074. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001302.

[49] Paul DK, Theivakularatnam M, Gnanendran CT. Damage Study of a Lightly Stabilised Granular Material Using Flexural Testing. Indian Geotech J 2015;45(4):441–8. https://doi.org/10.1007/s40098-015-0158-2.

[50] Piratheepan J, Gnanendran T, Lo S-C-R. Characterization of Cementitiously Stabilized Granular Materials for Pavement Design Using Unconfined Compression and IDT Testings with Internal Displacement Measurements. J Mater Civ Eng 2010;22(5):495–505. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000051.

[51] Pretorius PC, Monismith CL. Fatigue Crack Formation and propagation in pavements containing soi-cement bases. Highw Res Rec 1972;407:102–15.

[52] Rao Tangella SCS, Craus J, Deacon JA, Monismith CL. Summary report on fatigue response of asphalt mixtures. Berkeley, CA: Institute for Transportation Studies, Univ. of California; 1990.

[53] Sariosseiri F, Muhunthan B. Effect of cement treatment on geotechnical properties of some Washington State soils. Eng Geol 2009;104(1–2):119–25. https://doi.org/10.1016/j.enggeo.2008.09.003.

[54] Sobhan K, Das BM. Durabillity of soil cements against fatigue frature. J Mater Civ Eng 2007;19(1):26–32.

[55] Sounthararajah A, Bui HH, Nguyen N, Jitsangiam P, Kodikara J. Early-Age Fatigue Damage Assessment of Cement-Treated Bases under Repetitive Heavy Traffic Loading. J Mater Civ Eng 2018;30(6). https://doi.org/10.1061/(asce)mt.1943-5533.0002250.

[56] Sudla P, Horpibulsuk S, Chinkulkijniwat A, Arulrajah A, Liu MD, Hoy M. Marginal lateritic soil/crushed slag blends as an engineering fill material. Soils Found 2018;58. https://doi.org/10.1016/j.sandf.2018.03.007.

[57] Thompson MR, Smith KL. Repeated triaxial characterization of granular bases. Transp Res Rec 1990;1278:7–17.

[58] Tingle JS, Santoni RL. Stabilization of Clay Soils with Nontraditional Additives. Transp Res Board 2003;1819(1). https://doi.org/10.3141/1819b-10.

[59] Tran NQ, Hoy M, Suddeepong A, Horpibulsuk S, Kantathum K, Arulrajah A. Improved mechanical and microstructure of cement-stabilized lateritic soil using recycled materials replacement and natural rubber latex for pavement applications. Constr Build Mater 2022;347. https://doi.org/10.1016/j.conbuildmat.2022.128547.

[60] Udomchai A, Buritatum A, Suddeepong A, Hoy M, Horpibulsuk S, Arulrajah A, Horpibulsuk J. Evaluation of durability against wetting and drying cycles of cement-natural rubber latex stabilised unpaved road under cyclic tensile loading. Int J Pavement Eng 2021;1–12. https://doi.org/10.1080/10298436.2021.1950719.

[61] Vo ML, Plank J. Evaluation of natural rubber latex as film forming additive in cementitious mortar. Constr Build Mater 2018;169:93–9. https://doi.org/10.1016/j.conbuildmat.2017.12.098.

[62] Vollmert L. Reduction of accumulated plastic deformations in base courses. In: Green and Intelligent Technologies for Sustainable and Smart Asphalt Pavements. CRC Press; 2021. p. 579–82.

[63] Werkmeister S. Permanent deformation behaviour of unbound granular materials in pavement constructions. Ph.D. dissertation, TU Dresden, Dresden; 2003.

[64] Wilmot T, Rodway B. Stabilized pavements- Selecting the additive: cementitious, polimer or bitumen. In: The International Congress on Local Government Engineering & Public Works; 1999.

[65] Yaowarat T, Horpibulsuk S, Arulrajah A, Maghool F, Mirzababaei M, Rashid ASA, Chinkulkijniwat A. Cement stabilization of recycled concrete aggregate modified with polyvinyl alcohol. Int J Pavement Eng 2020. https://doi.org/10.1080/10298436.2020.1746311.

[66] Yaowarat T, Sudsaynate W, Horpibulsuk S, Chinkulkijniwat A, Arulrajah A, Horpibulsuk J. Mechanical properties of fly ash–asphalt emulsion geopolymer stabilized crushed rock for Sustainable pavement base. J Mater Civ Eng 2021;33(9):04021220.

BIOGRAPHY

Ms. Tran Thi Ngoc Quynh was born on July 01, 1989 in Quang Tri Province, Vietnam. She earned her Bachelor's degree in Engineering Geology and Hydrogeology from University of Sciences - Hue University, Vietnam in 2011 and then earned her Master's degree in Geology from the same University in 2013. Soon after graduating, she worked for Faculty of Geography and Geology, University of Sciences - Hue University as a lecturer. In 2019, she has been awarded a scholarship from the National Science and Technology Development Agency under the Chair Professor Program Grant No. P-19-52303, Suranaree University of Technology and Thailand Science Research and Innovation (TSRI) for her Ph.D. program in School of Civil Engineering, Institute of Engineering, Suranaree University of Technology, Thailand. During her Ph.D. study, she conducted research and wrote her thesis under the supervision of Asst. Prof. Dr. Menglim Hoy and Prof. Dr. Suksun Horpibulsuk. She has published 2 international journal papers, one in which as the first author and another as co-author, and had a presentation at International Conference on Innovation in Civil, Architecture, Environment and Materials Engineering (ICICAEME), Bangkok, Thailand, January 2023. She has also worked as a teaching assistant for School of Civil Engineering, Suranaree University of Technology during her Ph.D. study.